AGROMETEOROLOGICAL ASPECTS OF OPERATIONAL CROP PROTECTION

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AGROMETEOROLOGICAL ASPECTS OF OPERATIONAL CROP PROTECTION


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F O R E W O R D

Pests and diseases exact an appallingly heavy toll from world food production each year. The severity of attack by these organisms is often closely linked to weather. Recognizing this, the World Meteorological Organization has already sponsored directly, or through its Commission for Agricultural Meteorology, studies and reviews by working groups and rapporteurs, and seminars, which have resulted in a number of reports on specific aspects of the interaction between weather and pests and diseases (Bourke, 1955, 1961; Rainey, 1963; Hurst, 1975; Omar, 1980; Pedgley, 1980; WHO, 1963, 1965, 1969) (see Chapter 1 — References). There remained, however, the need for a wider-ranging investigation of the meteorological implications of pest and disease control. Therefore the Commission for Agricultural Meteorology at its eighth session set up a working group to study agrometeorological aspects of operational crop protection, with the following specific tasks:

(a) To define operational methods in disease and pest control in certain selected crops;

(b) To provide suggestions to facilitate the solution to problems encountered when methods are applied in regions with different agro-climates, with regard to genotype/environment interactions;

(c) To define needs for operational information (e.g. temperature, rainfall, wind and humidity conditions, upper wind conditions) for crop protection, both in quantity and quality, and to assess the economic importance of this information.

The Commission noted the special need to provide information which would be of value in the humid and semi-arid tropics.

The working group consisted of M. Davila-Zurita (Spain), Z. Gat (Israel), T.J. Gillespie (Canada), K. Konare (Mali), L.D. Lasso Espinosa (Colombia), G. Mathys (EPPO), D. Fayen (France), Z. Shengju (China), N. Thompson (UK) (chairman) and J.L. Van Hamme (FAO). The results of its work are reported in this Technical Note.

I take this opportunity to place on record the deep appreciation of the World Meteorological Organization for the time and effort devoted by the experts to the preparation of this Technical Note.

G.O.P. Obasi
Secretary-General
SUMMARY

The first part of this report provides a general description of the meteorological influences on plant diseases, on insect and weed pests, and on pesticides that are of importance to operational crop protection.

The consequent requirements for meteorological data in operational schemes are then presented, with the need for historical, as well as current and forecast weather information being outlined.

The results from a questionnaire sent to all Members, on the production and dissemination of crop protection information, form the basis of the following section. Many diseases and pests progress very rapidly in favourable meteorological conditions, and effective control measures have to be carefully timed. This requires not only rapid collection of meteorological data and their immediate use to produce crop protection advice, but also effective means of disseminating the advice. Developments in information systems such as Videotex are very promising in this respect.

A short section on the economic benefits likely to be gained by the use of agrometeorological information precedes the final chapter which draws conclusions and makes recommendations.

It is clear that even in the developed nations there is scope to greatly increase the use of agrometeorological information in operational crop protection schemes, especially forecast meteorological data. However, a major obstacle is that the response of the disease or pest to meteorological factors is often imperfectly understood. To develop optimal crop protection schemes requires closer collaboration than has usually been the case between biological scientists and agrometeorologists, both intra- and internationally, in order to make the best use of the always limited resources.

Unfortunately, much of the experience in operational crop protection which exists in developed countries cannot be readily transferred to the developing nations. There is a disparity in resources between developed and developing countries in terms of meteorological observing networks, data archiving and processing systems, the biological and agrometeorological scientists available and information dissemination systems, and also differences of climate, crops, and disease and pest species; indeed, many of the diseases and pests of importance to one set of countries simply do not occur, or are unimportant, to the other.
RESUME

La première partie de ce rapport décrit en termes généraux l'influence des conditions météorologiques sur les maladies phytosanitaires, les insectes ravageurs et les plantes adventices, ainsi que sur les pesticides couramment utilisés pour la protection des cultures.

Suit un exposé des données météorologiques qui doivent être fournies pour les systèmes opérationnels, notamment des données anciennes, ainsi que des informations sur le temps présent et prévu.

La section suivante a été établie à partir des réponses à un questionnaire envoyé à tous les Membres sur la production et la diffusion des renseignements en matière de protection des cultures. Beaucoup de maladies et de parasites se développent très rapidement lorsque les conditions météorologiques sont favorables et les mesures de lutte, pour être efficaces, doivent être planifiées avec soin. Il faut pour cela, non seulement rassembler rapidement les données météorologiques et les utiliser immédiatement pour fournir des avis sur la protection des cultures mais aussi disposer de moyens efficaces pour diffuser ces avis. Les nouveaux systèmes d'information, tels que Vidéotex, sont extrêmement prometteurs à cet égard.

La section qui précède les conclusions et les recommandations traite brièvement des avantages économiques que l'on peut tirer de l'utilisation des informations agrométéorologiques.

Même dans les pays développés, il serait à l'évidence possible de faire bien plus largement appel aux informations agrométéorologiques, notamment aux données météorologiques prévues, pour les systèmes opérationnels de protection des cultures. Toutefois, l'influence des facteurs météorologiques sur les maladies ou les parasites est souvent imparfaitement comprise, ce qui constitue un obstacle majeur. La mise au point de systèmes optimaux de protection des cultures exige une collaboration plus étroite entre biologistes et agrométéorologistes, au niveau tant national qu'international, afin de tirer le meilleur parti possible de ressources toujours limitées.

Malheureusement, une grande partie de l'expérience des pays développés en matière de protection opérationnelle des cultures ne peut être aisément transférée aux pays en développement. Cela s'explique non seulement par la disparité des ressources dont disposent ces deux groupes de pays - qu'il s'agisse des réseaux d'observation météorologiques, des systèmes d'archivage et de traitement des données, du personnel scientifique spécialisé en biologie et en météorologie agricole, ou des systèmes de diffusion de l'information - mais aussi par des différences de climat, de cultures, de maladies et de parasites; en fait, bon nombre des maladies et parasites importants dans l'un de ces groupes de pays sont tout simplement inexistantes ou sans importance dans l'autre.
РЕЗЮМЕ

В первой части настоящего отчета содержится обеое описание воздейстия, оказываемое метеорологическими факторами на болезни растений, на насекомых, вредителей и сорняков, а также на пестициды, которые играют важную роль в оперативной защите сельскохозяйственных культур.

Далее представлены вытекающие из этого потребности в метеорологических данных для оперативных схем, причем в обоих чертах описывается потребность в исторической, а также в текущей и прогнозической метеорологической информации.

В основе следующего раздела лежат ответы на разосланный всем Членам вопросник по получению и распространению информации для защиты сельскохозяйственных культур. Многие болезни и вредители развиваются очень быстро в благоприятствующих метеорологических условиях, а эффективные меры по борьбе с ними должны выполняться строго своевременно. Это обстоятельство требует не только быстрого сбора метеорологических данных и их немедленного использования в разработке консультаций по защите сельскохозяйственных культур, но также и эффективных средств распространения этой консультативной информации. В данном отношении развитие информационных систем, таких как "Видеотекст", является очень обещающим.

Заключительной главе, содержащей выводы и рекомендации, предшествует краткий раздел по экономическим выгодам, которые могут быть получены с помощью использования агрометеорологической информации.

Ясно, что даже в развитых государствах стоит задача существенного увеличения использования агрометеорологической информации в оперативных схемах защиты сельскохозяйственных культур, в особенностях данных метео-прогнозов. Однако основным препятствием является то постоянство, что зависимость болезней и вредителей от метеорологических факторов часто недостаточно понимается. Для разработки оптимальных схем защиты сельскохозяйственных культур требуется более тесное, чем обычно осуществимое, сотрудничество между биологами и агрометеорологами как на внутреннем, так и на международном уровне, с тем чтобы обеспечить наилучшее использование всего ограниченных ресурсов.

К сожалению, большая часть опыта, накопленного в области оперативной защиты сельскохозяйственных культур в развитых странах, не может быть перенесена целиком на развивающиеся страны. Это отражает не только разницу в ресурсах между этими двумя группами стран в смысле метеорологических национальных сетей, систем архивации и обработки данных, наличия ученых-биологов и агрометеорологов, а также систем распространения информации, но также различий в климате, в сельскохозяйственных культурах, их болезнях и вредителях: на самом деле многие важные болезни и вредители в одной группе стран просто не встречаются или не так важны в других.
RESUMEN

La primera parte de este informe contiene una descripción general de las influencias meteorológicas sobre las enfermedades de las plantas, las plagas de insectos y malas hierbas, y los pesticidas, que son importantes en la protección operativa de los cultivos.

Luego se exponen las necesidades consiguientes en materia de datos meteorológicos para los planes operativos, y se describe la necesidad de datos históricos e información meteorológica actual, así como sobre predicción meteorológica.

Los resultados del cuestionario enviado a todos los Miembros, que trataba de la producción y difusión de información relativa a la protección de las cosechas, constituyen la base de la sección siguiente. Numerosas enfermedades y plagas se propagan muy rápidamente en condiciones meteorológicas favorables, y es preciso programar cuidadosamente las medidas de control efectivo. Ello requiere no sólo la rápida concentración de datos meteorológicos y su uso inmediato para facilitar asesoramiento sobre protección de cultivos, sino también medios eficaces para transmitir dicho asesoramiento. A este respecto resultan muy prometedores los progresos realizados en los sistemas de información como el Videotex.

Una breve sección sobre los beneficios económicos que se podrían obtener probablemente mediante el uso de información agrometeorológica precede el último capítulo sobre las conclusiones y recomendaciones.

Es obvio que incluso en los países desarrollados hay campo para aumentar considerablemente el uso de información agrometeorológica en los planes operativos de protección de cultivos, y en particular de datos de predicción meteorológica. Sin embargo, un obstáculo fundamental consiste en que la reacción de la enfermedad o de la plaga a esos factores meteorológicos se comprende a menudo de manera imperfecta. Para poder elaborar planes de protección óptima de las cosechas es necesario que exista una colaboración más estrecha que de costumbre entre los biólogos y los agrometeorólogos, tanto a nivel nacional como internacional, con el fin de aprovechar de la mejor manera posible los recursos siempre limitados.

Desgraciadamente, gran parte de la experiencia que poseen los países desarrollados en materia de protección operativa de cosechas no se puede transferir fácilmente a los países en desarrollo. Ello refleja no sólo una disparidad de recursos entre ambos grupos de países en lo que se refiere a redes de observación meteorológica, sistemas de archivo y proceso de datos, biólogos y agrometeorólogos, y sistemas de difusión de información, sino también diferencias de clima, cultivo, enfermedades y especies de plagas. De hecho, muchas de las enfermedades y plagas que son importantes en un grupo de países, simplemente no existen, o son insignificantes, en el otro.
ACKNOWLEDGEMENTS

Substantial contributions to the report were provided by Dr F. Aparicio and Dr R. Coscolla (Plant Protection Service, Ministry of Agriculture, Spain), Dr W.N. Lablans (KNNV, Netherlands) and Dr I.M. Smith (EPPO), and are gratefully acknowledged.
CHAPTER 1

INTRODUCTION

1.1 POPULATION, FOOD AND RESOURCES

The world population has doubled during the last forty years, and is expected to double again by the 21st century. The highest rates of population growth are generally to be found in the developing countries, and are proving to be an increasing threat to world nutrition since it is in these countries that food supplies are already inadequate. In fact, at present, world food production continues to rise through the improving of crop varieties and cultivation methods, more intensive use of marginal land, and the extension of crop growing into previously virgin land. However, while the overall production increase has roughly matched the average population rise, it is not the case in many poorer nations where malnutrition is actually increasing (Swaminathan, 1979; Hartmans, 1983; Belshaw, 1984). The problem is being exacerbated by increasing desertification of once productive areas, caused in part by over-intensive grazing. In addition, within Africa, opportunities that used to exist for temporary population migration, in order to farm under-utilized or less arid land during times of drought, are often no longer available because of population pressure on all land.

It is generally accepted that most developing areas of the world have enough under-used land and water resources to feed adequately not only their present populations but also the substantially larger ones that will exist by the year 2000 (White, 1979). Bringing these resources into production will be costly, and in many cases will only come about through direct financial intervention by wealthier nations; any effective moves in this direction are likely to be sufficiently expensive to have a direct influence on the economies of the donor nations (e.g. through reduced living standards) and are unlikely to be carried through by those countries in the present political climate. How then can this situation be improved?

1.2 CROP LOSSES

Crop losses each year through pests and diseases are enormous: field losses in excess of 20 per cent occur regularly in many parts of the world (Cramer, 1967; Barr et al., 1975. Mulrooney, 1984) and storage losses are often at least as high (FAO, 1977a).

Reducing these losses would provide a method of matching food supplies to population needs in the immediate future. The impact of pests and diseases is particularly large in humid tropical regions where continuous cropping and high temperatures favour large populations of undesirable organisms (Wellman, 1972). In temperate latitudes, factors like winter breaks in cropping and lower temperatures usually lead to a smaller range of hostile organisms, and less severe attacks: even so, there have occasionally been very severe epidemics which have caused great hardship. For example, during the 1840s in Ireland, infestations of potato blight (Phytophthora infestans) caused famine and a major social upheaval resulted from the massive emigration that occurred during that period (Large, 1950).

1.3 PEST AND DISEASE CONTROL

Before the development of pesticides, deliberate control of pests and diseases was largely confined to cultivation in order to reduce weed
populations. However, it was probable that, through natural selection, many of the crop varieties grown had useful levels of resistance to insect pests and plant diseases; yields though were generally low. Chemical compounds then began to appear which, when applied to plants or soil, would control and sometimes almost completely eliminate pests and diseases, and farmers found that a notable improvement in productivity and profitability usually followed their use. As the arsenal of pesticides increased, plant breeders continued to produce higher-yielding varieties which, though not showing the natural resistance of many of the native species, could be grown very profitably when pesticides were applied. However, in many cases, only partial control was achieved, and when new generations of the pests or diseases appeared this situation quickly allowed these strains with most resistance to the pesticide to become dominant. Satisfactory control then required ever-increasing doses of chemical, eventually to levels which in some cases were 100 or even 1000 times larger than those originally employed. Examples of this build-up of resistance have been known for at least 75 years, and by 1980 nearly 400 species of arthropods with resistance to pesticides had been identified (Yousef and Service, 1983). In many cases, it proved impossible to maintain yields even with the use of enormous quantities of pesticide (as many as 50 applications a year in the case of Cotton Bollworm (Heliothis zea), which has become nearly immune to most insecticides (Luckman and Metcalf, 1975)) and alternative strategies have had to be developed: examples of these strategies have been given by Brader (1979), Yousef and Service (1983) and Salama (1983).

Weed pests in contrast have shown much less rapid development of resistance to herbicides, with for example, only nine resistant species reported by Parker (1977) when there were already more than 300 resistant insect species (Brown, 1977). However, continuation of the present high levels of herbicide use will inevitably lead to a build-up of resistance in more weed species and an increasing need for different weed control strategies in addition to the development of new herbicides. Many plant pathogens require much shorter times to complete each generation than weeds and therefore potentially shorter times to develop resistance to pesticides; as a result many pathogen species are now resistant to widely used pesticides. Although new pesticides continue to appear, the cost of their development and testing is very high and many eventually become too expensive for all but a few of the common diseases of high-value crops in relation to which a large market for the chemical can be assured.

That the control of pests and diseases by chemicals is by no means straightforward is borne out by experience of the USA (the world’s greatest user of these control tactics) (Table 1.1). Thus, Table 1.2 shows that in spite of a tenfold increase in the use of pesticides from 1941 to 1974, total pre-harvest losses due to pests showed no significant change. Pimentel (1978b) suggests that the main factors leading to the decline of the responsiveness of pests and diseases to pesticides, in addition to the build-up of resistance and the introduction of higher-yielding but less-resistant crops, are destruction of natural enemies, reduced crop rotation and diversity, and increased cosmetic standards (for instance in the case of fruit).

A further cause for concern stemming from the present enormous use of pesticides is the increasing risk of significant levels of pesticide residue in foodstuffs. The residues are now sufficiently important that many countries and organizations such as FAO, WHO and the EEC, have laid down legal standards or issued directives on permitted levels (FAO, 1977b; Coscolla, 1984). For economic, environmental and public health reasons any method which
TABLE 1.1

Present use of chemicals in crop protection (%)

<table>
<thead>
<tr>
<th>Area</th>
<th>Herbicides</th>
<th>Insecticides</th>
<th>Fungicides</th>
<th>Others</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>50</td>
<td>26</td>
<td>11</td>
<td>41</td>
<td>33</td>
</tr>
<tr>
<td>Western Europe</td>
<td>20.5</td>
<td>14.5</td>
<td>40</td>
<td>39</td>
<td>24</td>
</tr>
<tr>
<td>Japan</td>
<td>9.5</td>
<td>12.5</td>
<td>16</td>
<td>2.5</td>
<td>11.5</td>
</tr>
<tr>
<td>Eastern Europe</td>
<td>8.5</td>
<td>7</td>
<td>12.5</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Rest of World</td>
<td>11.5</td>
<td>40</td>
<td>20.5</td>
<td>10.5</td>
<td>22.5</td>
</tr>
</tbody>
</table>

TABLE 1.2

Pre-harvest crop losses in the USA. 1942-1974 (Pimental, 1978a)

<table>
<thead>
<tr>
<th></th>
<th>Insects</th>
<th>Diseases</th>
<th>Weeds</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1942-1951</td>
<td>7.1</td>
<td>10.5</td>
<td>13.8</td>
<td>31.4</td>
</tr>
<tr>
<td>1951-1960</td>
<td>12.9</td>
<td>12.2</td>
<td>8.5</td>
<td>33.6</td>
</tr>
<tr>
<td>1974</td>
<td>13.0</td>
<td>12.0</td>
<td>8.0</td>
<td>33.0</td>
</tr>
</tbody>
</table>

reduces pesticide use without decreasing pest control deserves whole-hearted support.

1.4 THE ROLE OF METEOROLOGY IN OPERATIONAL CROP PROTECTION

Because the development of many pests and diseases is influenced by weather, it is clear that agrometeorology can play a substantial role in crop protection. Through the use of pesticides, for example, proper utilization of operational meteorological information may result in not only fewer applications of chemicals, and hence slower development of resistance, but also better pest or disease control through better timing of sprays, and reduced environmental pollution. However, such goals are attainable only when the interactions between pest or disease and weather are properly understood: such information is still rarely available in the detail required for really effective, meteorologically-based spray programmes, even for the common pests and diseases of temperate latitudes. On the other hand, even when this detailed information is lacking, the use of meteorological data can ensure, for example, that spray drift is minimized, or that pesticides are applied at times when their activity is least reduced by weather factors.

1.5 FRAMEWORK OF THIS REPORT

The following four chapters discuss in turn meteorological aspects
of plant diseases, non-migrating and migrating insect pests, and weeds. Attempts are made to provide examples for a number of specific crops which, after consultation with the regional associations, were selected on the following bases:

(a) The crop should be economically important;
(b) The scale of attack by the crops, pests and diseases should have economic importance;
(c) Known schemes on plant protection should be available, or there should be a potential for such schemes;
(d) The crop should have global coverage;
(e) Sufficient published literature on the crop's pests and diseases should be available.

The chosen crops were:

- **Maize** - as recommended by CAGM-VIII;
- **Wheat** - a major food crop for which agrometeorologically-based plant protection schemes are available;
- **Sorghum/millet** - important as tropical food crops, with similar pest and disease problems; very few plant protection schemes exist for these crops;
- **Grape-vines** - an important cash crop with plant protection schemes;
- **Tomato** - a widely grown vegetable crop.

The next two chapters review the requirements for historical, current and forecast meteorological data on crop protection demonstrated by the earlier chapters. The important problems of how to produce information and warnings, and to disseminate operational information and advice are discussed. An attempt is then made to assess the economic importance to crop protection of agrometeorological information. The final chapter provides a summary and list of recommendations.
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CHAPTER 2

METEOROLOGICAL ASPECTS OF PROTECTION AGAINST PLANT DISEASES

2.1 INTRODUCTION

It has long been known that climate has a considerable influence on the development of crop pests and diseases, but it is only in this century that quantitative studies have been undertaken. As knowledge of the biology of crop predators and disease has improved, the extent of the influence of climate on the biological cycle and the activity of pathogens has become better known, and has been expressed increasingly in the form of quantitative relationships: in some cases it has been possible to produce more complex and comprehensive mathematical models that attempt to reflect the biology of pathogens, mainly as a function of climatic factors.

Such information is not only of considerable theoretical interest, which in itself would justify the research, but it also has a practical value in determining when action should be taken against crop pathogens, so that only those treatments that are strictly necessary are applied, at the most appropriate moment.

The effects of weather and climate on plant diseases are complex in that they are consequences of actions on the plant, on the pathogen and of their interrelations. There is general acknowledgement of the importance of climate; indeed, some plant pathologists have stated in the case of diseases for which the primary inoculum is always present, that it is climate which causes the disease in so far as the latter is only observed following favourable environmental conditions. The triangle of interrelations in Figure 2.1(a) is sometimes used to show the link between meteorological factors and disease, but this is a much oversimplified picture unless the influence of microclimate and soil is included (Figure 2.1(b): Lemee, 1978).

![Figure 2.1 Inter-relations between disease and climate](image-url)
A more detailed diagram (Figure 2.2) has been proposed by Rapilly (1982): he notes that in order to understand why disease epidemics spread with different speeds it is necessary to take into account:

- primary inoculum amount,
- climate/pathogen and climate/disease interactions,
- climate/growth interactions and development of the plant population.

![Diagram of disease epidemics](image)

Figure 2.2 External and internal pressures of a plant protection system (after Rapilly, 1982)

2.2 EFFECTS OF METEOROLOGICAL CONDITIONS ON EPIDEMIOLOGICAL SEQUENCES

Meteorological conditions influence each sequence of an epidemic, as shown by Rapilly (1983).

2.2.1 Primary inoculum

The amount of primary inoculum present is important for subsequent disease development. Jeger and Butt (1983) have demonstrated that meteorological conditions significantly influence winter dormancy of plant pathogens and therefore the inoculum present when growth recommences. This aspect (variation from year-to-year of the initial pressure of the disease) has often been neglected, especially in the cases of apple mildew, *Podosphaera leucotricha*, and scab, *Venturia inaequalis* for which winter temperature in particular is a controlling factor.
Another example is for the bacterium responsible for fireblight (Erwinia amylovora) that may overwinter in cankers that can be reactivated in the spring (Samson, 1973) and so contribute to an especially abundant inoculum in accordance with meteorological conditions.

2.2.2 Release and transport of pathogens

Climatic factors are involved in this phase in the cases of both actively and passively released organisms. Leach et al. (1977) have suggested that the following conditions are required for emission and dispersion of conidia of leaf blight of maize (Prechsiera turcica):

- a rapid decrease of relative humidity and increase of insolation
- wind speed above 3 m/s
- precipitation

It is also known that vapour pressure and photoperiod influence the release of D. turcica spores (Benedict, 1979). Wind of course plays a predominant role in dispersal, and is an essential input to mathematical models of dispersal such as those described by Gregory (1968).

There are many factors to consider in the cases of organisms which are released passively. Apart from the biological factors there are meteorological influences such as the duration and intensity of rain which for Septoria nodorum, for example, determine the amount of releasable conidia.

It is also necessary to take account of weather factors on insects whose activities may encourage the transport and dispersal of pathogens: wind speed, precipitation, temperature and insolation are of particular importance. Billing (1980) has described the risk of dispersal of fireblight inoculum by insects at fruit blossom time in terms of maximum temperature and insolation (Table 2.1).

**TABLE 2.1**

*Risk of dispersal of fireblight by pollen - and nectar - seeking insects (after Billing, 1980)*

<table>
<thead>
<tr>
<th>Max. temp (°C)</th>
<th>Low risk</th>
<th>Medium risk</th>
<th>High risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-17</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16-20</td>
<td>8-12</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>21-23</td>
<td>4-8</td>
<td>8-12</td>
<td>12</td>
</tr>
<tr>
<td>24-30</td>
<td>4</td>
<td>4-8</td>
<td>8</td>
</tr>
</tbody>
</table>

* Risk will be lower on wet or windy days
* Risk will be greatest if (a) there is abundant blossom (b) insect population is high (c) a favourable day follows unfavourable weather
2.2.3 Retention

The retention phase is important because it determines the quantity of inoculum collected by the sensitive surface. Rapilly and Pouault (1976) have shown that high relative humidity encouraged the adherence of spores of certain fungi to the surface of wheat leaves. Similarly, Yarwood (1977) noted that thermal shocks on maize leaves encouraged the retention of spores of *Puccinia sorghi*.

In certain cases an additional element is necessary for the development of the disease, for example the presence of rape petals adhering to the foliage for the infection of leaves by *Sclerotinia sclerotiorum* (Lamarque, 1983). In this case some moistening of the foliage is necessary for the petals to adhere but no washing rains and little wind.

2.2.4 Infection

Infection occurs when the organisms enter the plant, sometimes after a period of germination as in the case of fungal diseases. Infection is always possible while the plant is in a receptive physiological state, and the rate at which it proceeds is not usually strongly influenced by temperature, although powdery mildews, for example, are exceptions to this rule.

The limiting factor is often the absence of water on the plant surfaces, especially in the case of fungal pathogens, some of which must reside permanently in contact with water in order to survive. Numerous examples demonstrating the need for periods of wet weather for infection to proceed include one by Mah Shook Ying (1976) in the case of *Cochliobolus heterostrophus*: one of many examples showing a requirement for both high precipitation and humidity that given by Siradhanad et al. (1978) for *Sclerospora sorghi*. In many cases there is a requirement for a minimum period of surface wetness which, if interrupted, leads to loss of viability in the inoculum. A spectacular demonstration of this has been provided by Lamarque (1978) for *Sclerotinia sclerotiorum* for which the ascospores needed exposure to continuous wetness for at least 42 h, with temperatures around 20°C in order to infect the head of sunflowers: this severe condition explains the rarity of observed epidemics. One of the best-known set of relations between the minimum duration of leaf wetness for infection and temperature is that of Mills and LaPlante (1951) for scab (*Venturia inaequalis*, *V. pirina*) on apples and pears.

In operational plant protection schemes it is usually assumed that the infection conditions observed in the laboratory will be identical to those found in the field. However, in order to make direct use of this laboratory-derived information, it is necessary to measure the microclimate to which the disease is exposed in the field, or to infer it from meteorological measurements made outside of the crop. In a number of cases rules have been established or proposed which, explicitly or implicitly, relate conditions observed in the meteorological screen, and sometimes other standard observations such as rainfall, to leaf wetness: reported examples include Bourke's (1955) for potato blight (*Phytophthora infestans*) and Schroder and Fehrmann's (1971) for eyespot (*Pseudocercospora herpotrichoides*) of winter wheat. Micrometeorological models such as those of Payen (1983) for *Sclerotinia sclerotiorum* on sunflower, and Gillespie and Barr (1984) for dew on crops, have been developed for the same purpose.
2.2.5 Incubation

The main meteorological factors for incubation (as well as infection) are temperature, humidity and surface wetness.

The incubation of fungal diseases such as barley powdery mildew (Erysiphe graminis) depends mainly on temperature (Pauvert and de la Tullaye, 1977). For eyespot disease (Pseudocercosporella herpotrichoides) of soft winter wheat, the development of the pathogen is governed by temperature (Rapilly et al., 1979), although infection (of the base of the tillers in this case) requires at least 15 consecutive hours with relative humidity above 85 per cent, and temperature between 4 and 13°C (Schroeter and Fahrmann, 1971); in the case of the cultivar "Étoile de Choisy", for example, the daily disease development (D) can be represented by

\[
\begin{align*}
D &= 0 & T < 0°C \\
D &= 0.87(T+1.35) & T \geq 0°C
\end{align*}
\]

where \( T \) is daily mean temperature; when the accumulated value of \( D \) reaches 240 the first symptoms appear on the outsheaf, and the stalk is attacked for a value of 600, with total necrosis at 1200 accumulated units.

Other diseases such as fireblight (Erwinia amylovora) also show a strong relationship between development of the disease (bacterial) population and temperature (Billing, 1974). In this particular case, however, observations made in infected orchards and hedges in England (Billing, 1978) demonstrated that rainfall also needed to be taken into account because water (drought) stress may stop the multiplication of bacteria in the plant: Billing's proposed relationship to determine the incubation period therefore included data on both temperature and amount of precipitation.

Similar considerations apply to pathogens such as Septoria and Drechslera for which it is necessary to take account of plant wetness and relative humidity in order to estimate the incubation period.

2.3 PLANT DISEASE FORECASTING MODELS AND SYSTEMS

2.3.1 Introduction

Knowledge of the interrelations between environment, plant and disease continues to increase, and improvements in biological and meteorological data acquisition and processing systems appear regularly. These factors, along with advances in modelling techniques increasingly permit the employment of plant disease forecasting to facilitate pest management, achieving not only better disease control but also a reduction in the use of chemical products (Rapilly, 1980).

Distinctions need to be made, from both the operational and methodological points of view, between the different forecasting models or systems.

From an operational viewpoint, Touzeau (quoted by Gennatas, 1982) distinguished between two types of forecast models: (a) predictive models whose objective is to forecast the appearance of risk periods for crops and (b), quantitative models aimed at estimating the magnitude of these risks.
CHAPTER 2

The predictive models apply mainly to pests for which the tolerance threshold is nil or almost nil, the essential point, economically, being to avoid any depreciation of the harvested products so as to satisfy commercial or regulatory requirements. Such models therefore constitute an insurance for the grower. In the case of quantitative models, these are aimed at forecasting individual situations by simulating the dynamics of pathogen populations: they supply data enabling the grower to optimize his production costs and outputs so as to obtain the maximum profit from his operations. It is not a question in this case of an insurance but of a guide to good management.

From a methodological viewpoint there are three types of models (Rabbinge & Carter, 1983):

a) The analytical biophysical models, very comprehensive but used mainly for research purposes and requiring far too much data to be applied routinely;

b) Statistical models are mostly based on linear regression, but although they often give valuable information for decision making, their field of application is limited in time and space as they are empirical and not explanatory;

c) Dynamic simulation models are deterministic and explanatory models which can employ statistical methods, but within the framework of an analysis of the development processes of the diseases and of an identification of the different epidemiological sequences. The explanatory models fall into the latter category.

Besides these models in the strict sense, there are systems or rules, aimed most often at forecasting an infection period in terms of simple parameters or a synoptic analysis of the meteorological situation.

2.3.2 Examples

a) An example of a simulation model for a maize disease, corn leaf blight (Cochliobolus heterostrophus), is EPIMAY (Waggoner et al., 1972) which incorporates temperature, relative humidity, wind, wetness and insolation data on a three hourly basis; this model has been successfully used in Indiana (Shaner et al. (undated)).

b) A well known forecasting system is EPIPRE (Rabbinge and Rijndijk, 1983) which is a programme for controlling winter wheat diseases and pests, associating growers' observations and simulation models using meteorological data, in particular temperature and global radiation. The principal diseases concerned are yellow rust (Puccinia striformis), powdery mildew (Erysiphe graminis), and leaf and glume blotch (Septoria spp). A detailed description of this system is given in Appendix 2.1 in the format recommended by CARS (WCP, 1984).

c) A more empirical system is proposed by Castor et al. (1975) for forecasting the severity of attacks on maize by Stewart's bacterial disease (Erwinia stewartii) with the aid of a winter temperature index.
For apple scab, many systems have been proposed based on the integration of temperature and wetness duration data; the use of modern data processing methods has led to easily operable systems such as that described by Jones et al. (1980). It appears from the evidence that the measurement in situ, i.e., of the surface wetness duration in the actual foliage of apple and pear trees, allows a refinement of the precision of the systems for forecasting infection periods. Scab warning networks have been installed in France, notably in the Loire Valley (Olivier et al., 1983) and in the Rhone Valley (Gendrier, 1983), and also in the south-west.

d) Potato late blight (Phytophthora infestans) has been the subject of numerous infection period forecasting systems. The following may be mentioned:

i) The Dutch rules (van Everdingen, 1933): four conditions must be fulfilled for an appearance of the blight within 10 or 14 days: at least 4 h of night dew; a minimum temperature above 10°C; cloud cover exceeding 80 per cent the following day; and at least 0.1 mm of rain in the 24 h preceding the night dew;

ii) The Irish rules (Bourke, 1953): these lay down a 12 h period with a temperature exceeding 10°C and a relative humidity of over 90 per cent with at least 4 h of leaf wetness. If the period of leaf wetness is shorter, the relative humidity must exceed 90 per cent for 16 h;

iii) Beaumont's rules (1947): here the critical period which precedes the epidemic by seven to 21 days is defined by 48 h at least with a temperature exceeding 10°C and a relative humidity exceeding 75 per cent;

iv) The Norwegian rules (Forsund, 1983): the following parameters are considered: maximum temperature between 17 and 24°C, minimum temperature 10°C or above, relative humidity at 12 h of 75% or above and at least 0.1 mm of precipitation.

In these systems it is evident that the period of leaf wetness is inferred according to where the simple meteorological parameters are measured.

These simple systems are intended to give warnings for purposes of treatment. Other systems have been put forward using measurements in the fields and a computer supplying treatment advice: an example is BLITECAST (Krause et al., 1975) where the meteorological data required are the daily extreme temperatures, the number of hours with a relative humidity exceeding 90 per cent, the minimum temperature over that period and the amounts of precipitation.

The recognition of the difficulty of forecasting has led other authors such as Lomas (1983) or Schroder and Ullrich (1967) to propose negative forecasting systems, of which Primault (1983) gives an example used in real time.
2.3.3 Utilization

It is clear that models, systems or indices which forecast or evaluate plant disease risks have great value when used for warning or treatment advice purposes, as seen above. Many other examples exist, such as fungicide application advice in protecting carrots from *Alternaria dauci* (Gillespie and Sutton, 1979), but the successful development and use of all such schemes requires adequate understanding of the response of the pathogen involved to meteorological factors - even now this comprehensive information is available for only a few of the diseases which afflict the world's food crops.

The more general approach of using forecasts of meteorological situations which lead to an environment encouraging infection has also been adopted. Examples of this type of application of meteorological information have been given by Bourke (1955), and also by Nouallet (1981) who defined typical situations likely to lead to the prolonged moist conditions favourable to infection of sunflower heads by *Sclerotinia sclerotiorum*. One particular interest of this approach is that a forecast of this type of situation even 24 h ahead allows a preventative treatment which is more effective than a curative one. Additionally, these meteorological situations are often accompanied by heavy rain, so it is better to treat while spraying vehicles can move over the fields without damaging the soil structure, or becoming bogged down.

Other uses of the systems or indicators are possible. Thus when incubation is slow, monitoring of meteorological conditions permits early warning of possible disease problems. In the case of eyespot of winter wheat, it is possible to monitor the winter climatic conditions in order to supply plant protection services or growers with information on disease potential, in this instance the number of infections possible during the winter, and which may evolve subsequently as far as stalk necrosis. In France each year, a map showing the current potential for eyespot is published by the National Meteorological Service, and this alerts growers to increase crop monitoring in the spring if the disease potential is high.

Climate records extending back thirty years or so may be used with suitable models of disease development in response to weather factors to define geographical zones which are least favourable for growing the crop at risk. Examples include zoning of risks in France from *Sclerotinia sclerotiorum* on sunflowers (Gerber and Lobregat, 1981), and for eyespot of winter wheat (Rapilly et al., 1979). These simulation studies have been extended by Payen et al. (1983) by quantifying the influence of date of sowing on the potential for disease. Thus, sowing early at high density should achieve a high yield, but doing so increases the climatic risk of development of diseases such as eyespot, and so necessitates more careful control of the cropping cycle and, in particular, requires accurate rational timing of fungicide treatments.

2.3.4 Concluding remarks

A large number of plant diseases affect the world's food crops and reduce agricultural production. It is necessary to understand in detail the biological responses of these diseases to weather if rational, agrometeorologically-based crop protection schemes are to be developed and implemented: however, the required detailed information is rarely available,
even for some of the important diseases in developed countries. Nonetheless, useful schemes, though sometimes largely empirical, have been devised that use meteorological data to provide a proper basis for scheduling the application of chemicals. Much still remains to be done. Unfortunately it has to be recognized that experience in developing crop protection strategies in temperate regions, when winter conditions often provide a natural check to disease development, is not necessarily very relevant to disease problems in other regions where such climatic constraints may not exist, and where the biology of the diseases of interest may be very imperfectly understood.

In this chapter it has been possible to discuss only a few of the many plant diseases of economic importance, and then to illustrate various points which are important in the strategy and tactics of plant protection. It is hoped, however, that the outline provided has demonstrated not only the role of meteorological factors in plant disease development, but also how systematic use of such information in conjunction with operational and climatological weather data will lead to both improved crop production and more efficient use of pesticides.
REFERENCES


Lamarque, Cl., 1978: Conditions necessaires a la contamination des capitules de tournesol par Sclerotinia sclerotiorum. Proc. 8th International Sunflower Conference, Minneapolis.

Lamarque, Cl., 1983: Conditions climatiques qui favorisent le processus naturel de contamination du colza par Sclerotinia sclerotiorum (Lib.) de Bary. 6ème Congres International sur le colza, Paris, mai 1983.


REFERENCES


APPENDIX 2.1

CARS/Perd

INFORMATION ENRTY FORMAT

CARS entry no. 26

Date of entry 8 12 83

Last updated 8 12 83

d  m  y  d  m  y

1. OBJECT OF METHOD

1.1 Objective: Supervise pest and disease control incorporating existing
knowledge and leading to economically sound recommendations

Title: Epidemics Prediction and Prevention

to farmers (BC Countries).

1.2 Key words disease control wheat pest development

(from the list)

temperate _______ _______ _______ _______ 8. Crop-protection

Section Chapter

1.3 Other potential key words _______ _______ _______ _______

2. DESCRIPTION OF METHOD

2.1 Output (expected results and accuracy)

On an individual field basis, the system formulates recommendations to
farmers: (a) to apply a biocide within a certain period, if expected
yield loss exceeds economic threshold (if value of yield loss exceeds
cost of the treatment); (b) to supply the system with a new set of
observations within a specified period if it is a border-line case; (c)
to refrain from action if there is little or no expected damage.

2.2 Description

The system predicts the development of certain pests or diseases (yellow
rust (Puccinia striiformis), brown rust (P. recondita), mildew (Erysiphe
graminis), Septoria spp. and the cereal aphids Sitobion avenae,
Metopolophium dirhodum and Rhopalosiphum padi) for a given prognosis
period, the length of which is dependent on the phenological development
stage of the crop. From the predicted pest or disease development, an
expected yield loss is calculated, taking into account the type of
pathogen involved, phenological stage of canopy, yield expectation in
absence of pests and diseases, and weather expectations for the prognosis
period.

2.3 Input data

Meteorological data: Observed air temperature and global radiation
- Estimated air temperature (for each prognosis period)

Crop data: Crop variety, sowing data, sowing intensity, reports
by farmers of phenological stage and incidence of
various pests and diseases.
APPENDIX

Soil data: - Soil type

Management data:
- Information on previous crop, on fertilizer application (time and rate) on application of growth regulators (type and time) on application of biocides (type, rate and time).

2.4 Operational requirements (including computer requirements)
Operational on a number of computer systems.

2.5 Validity, limits imposed by basic concept constraints in application
Application of the system depends on willingness and ability of farmer to recognise the symptoms of most important pests and diseases. Success may be estimated from farmer's participation rate since he pays for the participation.

3. VALIDATION/PROVEN USES
Operational on a routine basis: Belgium, Switzerland, Netherlands Operational on an experimental basis: France, Sweden, England

4. REFERENCES
4.1 Author: Carter, M., Rabbinge, R. and Dixon, A.F.G.
4.2 Address: See 5.1 and other contacts (6. Remarks)

Date: 1982 Language: E Number of pages: 94

5. AVAILABILITY/SOURCES OF ASSISTANCE FOR FUTURE USERS
5.1 Contacts
R Rabbinge, Dept. of Theoretical Production Ecology, Agricultural University, P.O. Box 14, Wageningen, The Netherlands.

5.2 Nature of assistance available.

6. REMARKS: Additional references:

Additional contacts:

J.C. Zadoks or R.H. Rysdyk, Phytoconsult Ltd. Wageningen, The Netherlands.

K. Reinink, Experimental Station for Arable Crops and Horticulture (PAGU), Lelystad, The Netherlands.
CHAPTER 3

METEOROLOGICAL ASPECTS OF PROTECTION AGAINST INSECT PESTS

3.1 INTRODUCTION

The climatic factor which has by far the greatest influence on the development of insect pests is temperature. Other climatic factors which have a marked influence include relative humidity, rainfall, wind, light and drought, and these also will be considered in relation to certain pests.

The main part of this chapter examines in detail the meteorological factors affecting selected "key" pests of maize, grapevines and cotton. Because of the enormous losses of stored crops to insects, a brief discussion is also included of some important storage pests of cereals.

3.2 PESTS WHICH AFFECT THE MAIZE CROP

3.2.1 Introduction

3.2.1.1 Distribution

Maize is a crop which is grown over all continents (from 58° latitude north, in Canada and Russia, to 40° latitude south), at different altitudes (from those below sea-level in the flat lands of the Caspian Sea, to 3,600m in the Peruvian Andes), in areas of different rainfall patterns (from 250 mm/year in the semi-arid Russian flatlands to more than 1600 mm on the Pacific coast of Colombia), and in places which have a short summer (Canada) or a permanent summer (the tropical regions of Ecuador and Colombia, etc.). Consequently, the incidence of pests varies greatly from one region to another because of the enormous variation in growing conditions.

However, insect pests exist -- of both the devouring kind, such as the larvae of the moths Ostrinia nubilalis, Heliocis sp. and Spodoptera sp. etc., and plant-eating types, for example the aphid Rhopalosiphum maidis -- which are present in most of the regions where maize is grown. On the other hand, other insects are more localized and constitute a pest which is peculiar or specific to a certain region, for example in some areas of Europe and Latin America the larvae of Agriotes sp. or the aphid Myzus sp. Sometimes there are pests which are present in just one country. In short, they can be considered as general, or local in their distribution.

3.2.1.2 Quantitative extent

There are no precise data on the losses which are caused by the insect pests of maize on a world scale. Some countries, especially the United States, publish some annual statistics on losses caused by pests in the field and during storage, although the figures are normally based more on the opinion of experts than on precise experience.

In the United States losses caused by insects are put at an annual 12 per cent of potential production, in spite of the extensive use of pesticides. At world level it is estimated to be 12.4 per cent of potential production. This represents 66.5 million tonnes of grain. The total figure for losses which occur in maize as a result of pests, diseases and weeds as a
whole amounts to about 35 per cent of potential production, i.e. 186 million tonnes of grain (FAO, 1980).

3.2.1.3 **Pests in the field and during storage**

There exist, in addition to the insects which attack maize in the field (the main concern of this chapter) a great number of insects which may attack grain during transportation and storage. These can be particularly prevalent in those areas such as the developing countries where storage places are often inadequate. In these cases, the losses after harvesting may be higher than those suffered during cultivation in the field.

3.2.1.4 **A picture of the main insect pests at world level**

Table 3.1 (FAO, 1980) indicates the main pests according to the continent where they are present, and the type of harmful activity involved. In addition to this basic general outline, it is necessary to consider in some cases other particular factors which may have an effect on the damaging nature of the insect pests: these include the possibility of feeding or sheltering in alternative hosts, the concurrence of species and the possibility of diseases being transmitted (some aphids are virus carriers).

The basic idea which will be pursued is that climatic factors play a fundamental role in determining whether or not an insect might constitute a pest, by affecting population levels, for example. These factors come to the forefront when they assume extreme values and drastically limit the insect populations, but they also have a direct influence on the insect’s biological potential and the limiting biotic factors.

3.2.1.5 **The key-pests**

Numerous insect species may attack maize (Table 3.1, which could be expanded further by including localized pests), but only a few species normally attain the level of a pest and require intervention to control them. The majority cause negligible damage or none at all and only occur sporadically. Those species which occur habitually and cause extensive damage if measures are not taken against them are called key-pests: The strategy of applying plant-health protection is usually directed towards them. Secondary pests on the other hand (also referred to as occasional pests) are those which only occasionally reach the economic threshold of damage: even then action is required only when circumstances favour a further increase in their populations.

Key-pests and secondary pests in the main maize-producing country, the United States, are listed in Table 3.2. This division between secondary and key pests is not fixed: if conditions alter a key-pest may become secondary or a secondary pest may become a main pest, and so the latter must always be seen as representing a potential danger.
<table>
<thead>
<tr>
<th>AFRICA</th>
<th>AMERICA</th>
<th>ASIA</th>
<th>EUROPE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PLANT- SUCKERS</strong></td>
<td><strong>DEFFECTORS</strong></td>
<td><strong>EARS</strong></td>
<td><strong>STEM BORERS</strong></td>
</tr>
<tr>
<td>Rhopalosiphum maidis</td>
<td>Schistocerca gregaria</td>
<td>Heliothis armigera</td>
<td>Chilo partellus</td>
</tr>
<tr>
<td>Pseudogrylloblastus maidis</td>
<td>Locusta migratoria</td>
<td>Pyroderces sp.</td>
<td>Ostrinia nubilalis</td>
</tr>
<tr>
<td>Cicadulina spp.</td>
<td>Zonocerus variegatus</td>
<td>Pseudocepta ablinea</td>
<td>Sesamia cincta</td>
</tr>
<tr>
<td>Dysdercus superbus</td>
<td>Epilachna sp.</td>
<td>Pococera atramentalis</td>
<td>Z. cincta</td>
</tr>
<tr>
<td><strong>DEVOURERS OF BASE OF STEM AND SEEDLINGS</strong></td>
<td><strong>ROOT EATERS</strong></td>
<td><strong>LICHTER</strong></td>
<td><strong>AUKITIS</strong></td>
</tr>
<tr>
<td>Marasema spp.</td>
<td>Phytophaga spp.</td>
<td>Loxostegia sticticalis</td>
<td><strong>AUKITIS</strong></td>
</tr>
<tr>
<td>Spodoptera littoralis</td>
<td>Astylus atrimaculatus</td>
<td>Leithenus asiaticus</td>
<td>Elateridae</td>
</tr>
<tr>
<td>S. exigua</td>
<td>Elateridae</td>
<td>Leptotylus orientalis</td>
<td>Bynocrypta pertenaea</td>
</tr>
<tr>
<td>S. erugula</td>
<td>Termites</td>
<td>Athripsodes orientalis</td>
<td>P. gallarum</td>
</tr>
<tr>
<td><strong>AUKITIS</strong></td>
<td>Heteronychus spp.</td>
<td>Holotrichia consanguinea</td>
<td>Hylemya platura</td>
</tr>
<tr>
<td>A. atrimaculatus</td>
<td></td>
<td>Leucopis irrorata</td>
<td>Agrotes sp.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aphegma spp.</td>
<td></td>
</tr>
</tbody>
</table>
TABLE 3.2

Insects considered to be of primary and secondary importance for maize crops in the United States (FAO, 1980)

<table>
<thead>
<tr>
<th>Pests of primary importance</th>
<th>Pests of secondary importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Corn Borer</td>
<td>Maize-ear worm</td>
</tr>
<tr>
<td>(Ostrinia nubilalis)</td>
<td>(Heliothis zea)</td>
</tr>
<tr>
<td>Western Corn Rootworm</td>
<td>Grasshoppers</td>
</tr>
<tr>
<td>(Diabrotica Virgifera)</td>
<td>(Melanoplus sp)</td>
</tr>
<tr>
<td>Northern Corn Rootworm</td>
<td>Thrips</td>
</tr>
<tr>
<td>(Diabrotica longicornis)</td>
<td>(Limothrips cerealium)</td>
</tr>
<tr>
<td>Maize-leaf aphid</td>
<td>Mites (acarids)</td>
</tr>
<tr>
<td>(Rhopalosiphum maidis)</td>
<td>(various species)</td>
</tr>
</tbody>
</table>

3.2.2 The influence of climatic factors

3.2.2.1 Selection of a model key-pest: justification

There are numerous published works which refer, directly or indirectly, to the action of climatic factors on the various pests that infect maize plants. However, for conciseness the criterion of studying in some depth the influence of climatic factors on a basic key-pest will be adopted, using a descriptive method that can serve as a model when a similar study needs to be carried out on other pests.

The basic key-pest chosen for study is the pyralid moth Ostrinia nubilalis Hbn. The reasons for this choice are:

(a) It is a key-pest in most of the areas of the world where maize is grown, extending over all continents, causing a great volume of damage and normally requiring action to limit its effects

(b) The effects of climatic factors on the insect have been studied in detail. The literature is abundant and in addition the climatological aspects (temperature, humidity, wind, rain, photoperiod, etc.) and the developmental aspects of the insect are well covered.

The following discussions draw extensively from the reviews by Balachowsky (1972) and Arias and Alvez (1975), supplemented as far as possible by later publications referring to the subject.

3.2.2.2 Analysis of the action of various factors on Ostrinia nubilalis Hbn

3.2.2.2.1 Distribution of O. nubilalis throughout the world

O. nubilalis is an insect which is present in all five continents and is able to live in different climatic conditions (temperate, Mediterranean,
sub-tropical, tropical and equatorial), being especially prevalent in the northern hemisphere. As Caffrey and Worthley report (1927, quoted by Balachowsky, 1972), *O. nubilalis* tolerates weather conditions which are as different as the dry steppes in the south of European Russia (mean annual temperature of 7°C and annual precipitation of 330 mm), or those of the island of Guam (Marianas) (mean annual temperature of 27°C and annual precipitation of 2500 mm).

3.2.2.2 Biological cycle in the different regions of the world

The annual cycle of *O. nubilalis* comprises from one to six generations depending on geographical location in the world: in the northern hemisphere, where the insect is most widespread, the number of generations is largest near the Equator.

In temperate climates, where there is only one annual generation, the development is as follows: spring nymphosis in May-June, flight of the adults and egg laying in June-July, development of larvae from June-October and diapause from September-October to May-July in the form of a fifth-stage larva. When the climate is warmer several generations a year develop continuously during spring, summer and autumn, but there is always a larval diapause during the cold season.

There is no abrupt separation between neighbouring regions with different cycles, but there are transition zones where intermediate situations occur. Thus, for example, in the transition zones between univoltinism and polyvoltinism, a variable percentage of first-generation larvae go into diapause, whilst others pupate and give rise to a second-generation which consequently has mixed characteristics.

Concentrating on the northern hemisphere, where it has been most studied, in Europe there is only one generation in the northern, central and eastern regions. France is intermediate in nature since in the north there is one generation whilst in the south there are two generations (Robin, 1980). In Spain there may be one generation (Galicia), two generations (in the fertile lowland around the River Ebro) or three generations (in most places) (Arias and Alvez, 1975). In the USSR there is one generation in the more northerly regions of maize cultivation, and two generations in the Caucasus and Crimea (Ellinger, 1928).

In China there are three or four generations in Yunnan and six generations in Kwang-si. On the island of Guam (Marianas) there are five generations.

In the United States there is only one generation in the centre and north of the corn belt (Pennsylvania, Wisconsin, Ohio, Indiana, Kentucky and Michigan), two generations in the east (New Jersey, Connecticut, Maryland, New Hampshire, Massachusetts, Iowa and Oregon) and three generations in the south and south-eastern states (Alabama, Virginia, etc.).

In Canada there is normally one generation, but more recently cases of two generations have been reported (McLeod et al., 1979).

It will be shown that climatic factors have a determining role in the number of annual generations. However, it should be noted that, in addition to the influence of the environment, it is necessary to consider the
influence of heredity. Thus, US and more recently Canadian workers have shown the existence of biologically distinct races, some univoltine and others bi- or polyvoltine. The simultaneous presence of two races of different voltinism in same region may explain the existence of transition cycles with a partial generation. Thus, for example, in Canada the presence of two races of O. nubilalis have been reported: the normal one, with one generation a year and another recently introduced race with two generations a year. The latter has a quicker diapause, emerging earlier in the spring and the critical photoperiod for going into diapause is shorter. The characteristics of both races have been well defined through laboratory studies and response to pheromones (Moore et al., 1979).

### 3.2.2.2.3 Action of temperature

#### (a) General aspects

The action of temperature on the development of *O. nubilalis* has been studied in detail and the literature produced is extensive; only a few examples will be given here.

As in all insects, critical temperatures exist (lower and upper), as well as development thresholds, which are different according to the stage of the insect. Moreover, the rate of development of the insect is dependent on temperature, its development increasing as the temperature rises. A graph relating temperature and duration of development is usually a hyperbolic curve (Sanderson and Pearse, 1913; Bodenheimer, 1926; Pearse, 1927). Correspondingly, the relationship between rate of development and temperature is a straight line (Janisch, 1930; Caffrey and Worthley, 1927; Wigglesworth, 1950; Mateson and Decker, 1965). This "rate of development straight line" can only be applied between the lower and upper temperature limits that apply to each phase of the insect.

A consequence of this relationship is that the number of generations is linked to temperature. Thus in the Far East, Clark (1934) reports that the number of generations depends on the number of months in the year when the normal average temperature exceeds 15.6°C, so that there would be only one generation in regions where in only three months of the year the required average temperature is exceeded and there would be at least three complete generations where this period exceeds seven months. These results were confirmed by their use by Fahmy (1936) in Egypt to explain the four annual generations of *O. nubilalis*.

Apple (1952) and Chiang and Hodson (1959) showed that temperature accumulations above a certain threshold (e.g. 10°C) could be used to predict nymphosis, and the time of appearance of the various stages of the insect during the period of maize cultivation. It should be pointed out, however, that the interaction between the factors of temperature and photoperiod also have a determining role on voltinism (see section 3.2.2.2.7).

#### (b) The influence of temperature on the adults

The temperatures most favourable to flight, which is nocturnal or crepuscular, are situated between 21°C and 24°C according to Harvey and Palm
(1935), or between 18°C and 21°C (Stirrett, 1938), the temperature threshold of flight for the former being 15°C and for the latter 13.5°C.

According to Beall (1938) the number of adults observed during night-time is proportional to the maximum daytime temperature: maximum trappings were recorded when during the main hours of flight (between 22 h and 24 h) the temperature was 18°C and relative humidity 90% (Guennelon and Audemard, 1960).

Laboratory studies have been carried out on the frequency of movement of the wings, the speed of flight and the duration of flight in relation to temperature: in the field, it has been found that the lower thresholds of flight can be a factor in the determination of the limits of its vertical distribution, the duration of flight and migratory distance (Carpenter et. al., 1982).

The influence of temperature on longevity and fecundity of the adult is considerable. In laboratory experiments the optimum conditions for egg-laying females are 29°C and 96 per cent relative humidity, at which they live for 10.8 days and lay 823 eggs on average (Vance, 1949). Longevity and fecundity decrease in direct proportion to temperature and relative humidity, ceasing at 15°C.

(c) Influence of temperature on the egg

The temperature limits for the development of the eggs of *O. nubilalis* were placed at between 9-10°C and 35°C by Kozhanovich, (1938), but Guennelon and Audemard (1960) situate the lower threshold at 12-13°C and Matteson and Decker (1965) put it at 14°C, all from laboratory tests. The last authors report the most favourable temperatures as being between 18°C and 27°C (Figure 3.1).

(d) Influence of temperature on the larvae

In laboratory tests at constant temperature (Matteson and Decker 1965), the normal range of development of the larvae was from 15 to 32°C, with the threshold at 11°C (Figure 3.2).

![Figure 3.1 Duration in days of the incubation of *O. nubilalis* eggs at different controlled temperatures](image)
The larvae spend the winter in diapause in the last stage of development and so they are very resistant to cold. As a consequence, mortality through frosts or cold winter weather have little effect on the reduction of the populations of the insect in zones with a temperate or southern climate, even on days of very cold weather (as demonstrated by Stirrett, 1928, in Canada, and Guennelon and Audemard, 1960, in France). Only in the northern regions can the winter cold prove fatal for them. Thus, for example, in Sweden accidental infestations of O. nubilalis have never prospered for this reason (Borg, 1947).

The first laboratory experiments to determine resistance to winter cold were carried out in the USA. Caffrey and Worthley (1932) determined that the exposure conditions which were fatal for all insects exposed to them were 10 minutes at -35°C, 12 minutes at -29°C, 20 minutes at -23.3°C, 2½ hours at -17.8°C, and 65 hours at -9.4°C. If the larvae were inside tunnels, as is normal, eight days at -17.8°C were necessary to cause death.

The subject was subsequently studied in more detail by Barnes and Hodson (1956) and Beck and Haneec (1960). Many insects can cool down to temperatures lower than their freezing point without ice forming in their tissues because of subfuson, but, in addition, O. nubilalis can spend the winter alive in tunnels surrounded by ice, being even more resistant in dry shelters.

Figure 3.2 Duration in days of the larval development of O. nubilalis

The degree of resistance to cold of the larvae of O. nubilalis varies throughout the insect's period of repose, it being sensitive to cold at the beginning of autumn when it cannot survive several days at subfusion temperature (Haneec and Beck, 1960). The point of subfusion decreases progressively throughout the autumn at the same time as tolerance of cold increases. When this point reaches -20°C the larvae can withstand three months at this temperature if they are not in high humidity. The point of subfusion may reach -29°C, when Barnes and Hodson found that exposures of 22 days at -32°C which did not affect the survival rate of O. nubilalis. In spring the subfusion point slowly increases, but until -20°C is exceeded the larvae are still very resistant.
At the other extreme, i.e. at abnormally high temperatures, temperatures exceeding 32°C for several days may begin to affect the young larvae (Barbulescu, 1982). As they grow older they become more resistant, as has been demonstrated in laboratory studies carried out to determine the effects of a short exposure (up to 12 hours) at an upper temperature limit (45°C) on the neuro-secreting cells in larvae which were in diapause and on their survival rates (Glumac et al., 1979).

(e) Influence of temperature on chrysalids

As in the other stages, the length of pupation varies with temperature. In laboratory tests the normal temperature range for the development of chrysalids is 15 to 29°C, and the threshold is 12°C (Matteson and Decker, 1965: Figure 3.3).

In almost every year, in south-east Minnesota (USA) a second partial generation occurs, i.e. a varying percentage of first-generation larvae pupate throughout August instead of going into diapause. In a study covering 11 years it was found that there was a correlation between the years with high or low degree day accumulations (above a base of 10°C) by July and the high or low pupation rates in August (Chiang and Hodson, 1959).

Moreover, the spring emergence of adults from chrysalids and consequently their flight curve is considerably influenced by temperature, both from the point of view of the temperature level reached and the degree-day accumulations. Thus in Italy, Coppolino (1979) found a relation between the accumulated frequency of emergence and the accumulated temperature; in this way it is possible to make predictions with regard to the evolution of flight. Also in Ohio (USA) Clement et al. (1981) proposed predictions of spring flight on the basis of temperature. In Canada, McLeod (1981) used a multiple-regression analysis to establish that meteorological parameters were important in determining the spring flight of O. nubilalis. Using simple equations to calculate the emergence as a function of degree-days, practical results with good accuracy were obtained.
Lastly, temperature may also influence the survival of the chrysalids, since very high temperatures accompanied by dry conditions are fatal to them (Stirrett, 1938). Thus, according to laboratory experiments the mortality rate amounts to 84 per cent, 20 per cent, 25 per cent and 100 per cent at temperatures of 12°, 20-30°, 32° and 35°C respectively.

(f) Corollary regarding temperature

Temperature is seen to be a fundamental climatic factor for the development of the insect's cycle, since on the one hand it determines its length (and consequently the number of generations and the times at which attacks will occur), and also the density of pest population: as such it can be an important factor in mortality or survival, and even determining whether the pest will be present or not in certain countries. It has, therefore, a decisive influence both from the quantitative point of view and from the qualitative or phenological point of view, the latter being summarized by Figure 3.4 (Matteson and Decker, 1965).

![Figure 3.4](image)

Duration in days of all the immature stages of *O. nubilalis* at different controlled temperatures.

Obviously laboratory tests are carried out at constant temperatures but in the field there are daily temperature fluctuations, and so there could be errors if the laboratory data are extrapolated using only daily average temperature. Matteson and Decker (1965) found that even though this means some acceleration compared with laboratory data, it is very small. Thus, the concept of accumulated temperature (the sum of average daily temperatures above the insect's threshold of development, fixed usually at approximately 10°C) which has been used by several authors in various countries to predict the appearance of the separate phases of the insect's development (so modelling its cycle) is very important in practice, since it can be used to determine the times when action should be taken against this pest.

3.2.2.2.4 The effect of relative humidity

Relative humidity influences *O. nubilalis* in several ways. First, it affects the flight of adults and their egg-laying activity. Thus
Kozhanchikov (1937) was not able to observe any egg-laying in the laboratory below 70 per cent RH the optimum conditions for laying being at around 100 per cent RH. He also noted that the females were not very fertile if they came from chrysalids which had been subjected to very dry conditions. Vance (1949) suggested 96 per cent RH as the optimum for egg-laying. Guennelon and Audemard (1960) recorded extensive trappings of adults on a night when the relative humidity was 90 per cent.

Relative humidity is also an important factor in determining the mortality of eggs, which generally speaking is high in natural conditions (Guennelon & Audemard, 1960). In laboratory conditions Kozhanchikov (1938) in a study of the influence of humidity combined with temperature on embryonic mortality, concluded that the eggs of *O. nubilalis* require a moist environment. At 100 per cent RH all the eggs hatched out between 17.5°-30°C. At 90 per cent RH all the eggs hatched out only when the temperature was 25°C. Mortality increased further at 80 per cent RH, but at 25°C it only reached 6 per cent. At 75 per cent RH no egg hatched out at any of the temperatures tested except at 25°C when the mortality rate was 17 per cent.

Stirrett (1938) also reported that the eggs do not develop during hot, dry periods, and Ladvisenskaya (1937) found that when relative humidity was low during the day (30 per cent-40 per cent) about 25-30 per cent of the eggs did not hatch. The majority of authors agree that the natural mortality rate of eggs depends mainly on the dryness of the air.

Larvae when studied in the laboratory also require high humidity (95-100 per cent) in order to survive (Kozhanchikov 1938). This does not present a problem in the wild since they are inside the plant's stem in a constantly humid environment. Here though, moisture in the form of dew or drizzle may accumulate in the leaf axils in sufficient amounts to cause death through drowning.

It has also been reported that humidity has an influence on the hibernating larvae's emergence from diapause and it has been possible to demonstrate that the larvae drink water before pupating (Mellamby, 1958). Babcock (1927) reported that pupation is retarded when larvae are kept in a dry environment, and that diapause may not come to an end if the larvae are dehydrated unless their photoperiodic requirements have been met: conversely pupation does not take place in the case of partially dehydrated larvae even though they have been exposed to long days (Beck, 1967).

Humidity also influences the survival or mortality rate of the chrysalids of *O. nubilalis*. Thus, the chrysalids are capable of developing at relative humidity between 25 per cent and 100 per cent, the optimum being 100 per cent (the mortality rate is then at its least: 20 per cent). The pupae kept at this high humidity give rise to females which are more fertile than average (Kozhanchikov, 1937, 1938).

3.2.2.2.5 The effect of rain

Rainfall inhibits the flight of adults if it is sufficiently intense. Thus it has been reported in the USA that rainfall in excess of 3.5 mm per hour prevents the flight of adults (Stirrett 1938). Studies in France showed that abundant rainfall prevented flight (Guennelon and Audemard, 1960).

Recently it has been reported that the adult population of *O. nubilalis* is not normally reduced by precipitation alone but, when accompanied
by strong winds, the population levels may be drastically reduced (Sappington and Showers, 1983). Where rainfall can act as an important factor in mortality is on the new born larvae, i.e. during the first few days following the hatching of eggs when together with wind it can cause mortality rates of up to 75 per cent (Painter and Fich, 1924). Recently, in Romania, it was found that heavy rainfall, together with hailstones, drastically reduced the populations of *O. nubilalis* when this precipitation occurred during the period of the eggs hatching and the first larval stages (Barbulescu, 1982).

3.2.2.2.6 Action of the wind

Strong winds may impede the normal flight of adults (Guenelon and Audemard, 1960), although it has been reported that winds around 7 m s⁻¹ do not affect flight (Stirrett, 1938). It has been mentioned already that strong winds accompanied by rain can cause important reductions in the adult population. Winds varying from 8 to 18 m⁻¹, depending on the intensity of the precipitation were found to be very destructive (Sappington and Showers, 1983). Additionally, the eggs laid can be wrenched from the leaves of maize by violent gusts of wind, such as occur with the mistral in France (Balachowsky, 1972). Lastly, although the wind enables the young larvae to be disseminated, it also causes great mortality owing to its violent mechanical action when they are newborn (Balachowsky, 1972).

3.2.2.2.7 The effect of the photoperiod

It has been noted earlier that the number of generations each year depends on whether the larvae which have reached the final stage of development pupate or go into diapause. The transition to diapause depends basically on the interaction of temperature and photoperiod (Mitchmor and Beckel, 1959; Beck and Apple, 1961; Beck and Hanoc, 1960; Beck 1962, 1968 and 1982; Bonnemaison, 1978; Gelman and Hayes, 1980; Robin 1980).

The induction of diapause in *O. nubilalis* by the photoperiod is the so-called short-day/long-day mechanism. Thus diapause is not induced on very short days or very long days, but is complete on intermediate days (between 10.5 and 13.5 hours long). There are critical daylengths outside this range where small variations in the length of the day cause great variations in the percentage of diapause, in the passage from short days to medium days (between 8 and 9 hours), and for decreasing daylength (between 16 and 15 hours).

The length of the critical day is not unique, since the diapause depends not only on that but also on the temperature: it has been shown that high temperatures tend to reduce the percentage of diapause in short photoperiods and thus the length of the critical day is from 16 h. to 15 h. 30 m. for temperatures of 23° C and from 15 h. 30 m. to 15 h. for temperatures of 20°C and less.

Diapause is a temporary stage of suspended development, determined genetically, but it is clear that populations of *O. nubilalis* are heterozygotic in relation to multiple genetic factors controlling the response to the photoperiod. The adaptation of *O. nubilalis* to the particular local temperature and photoperiod conditions may lead, through a process of natural selection, to an inherent change in the frequency of the genetic factors which control the response to the photoperiod. In short, although the ability to go into diapause is determined genetically, the environmental factors, and especially the photoperiod, have a decisive influence on the manifestation of this optional diapause.
3.2.2.2.8 The indirect influence of climate.

In addition to the direct action of each one of the climatic factors on the biology of *O. nubilalis*, these same climatic factors can also have an indirect action by influencing factors that in turn have an influence on the biology of *O. nubilalis*.

- The influence on the plant

The development of the maize crop in a particular year and zone is dependent on climatic factors, to the point that models for predicting development and yield have been drawn up based mainly on meteorological parameters, such as CORNF (quoted by Parsons et al. 1981). It is clear that the influence on the life of *O. nubilalis* of the plant's development will be appreciable since the plant is the insect's material support and food. Thus, for example:

The state of growth of the maize plays an important role in determining the insect's egg-laying, since the height of the plants is an essential factor. Numerous authors report that the insect lays eggs only on maize which has exceeded a minimum size, between 35 and 45 cm (quoted by Balachowsky, 1972).

A non-limiting supply of water maintains the development and turgidity of the plants, and so increases their nutritional value for the larvae, hence facilitating their development and even indirectly affecting the fertility of *O. nubilalis* (Rumyantzev, 1939).

An alternation of warm days and cold nights may cause an alternation between some degree of wilting of the leaves and turgidity of the latter which can be the mechanical cause of "egg-plates" falling and the eggs dying (Stirrett, 1938).

It follows that the biological cycle of *O. nubilalis* can be disrupted by varying the climatic conditions of maize-growing, for example by altering the date of sowing and controlling soil wetness through irrigation.

Conversely, a correcting function should be included in crop models to account for expected damage by *O. nubilalis* (Parsons et al., 1981).

- Effects of parasites of *O. nubilalis*

Important factors in reducing the natural populations of pests are their natural predatory and parasitic enemies. The effectiveness of these parasites is dependent, amongst other factors, on their population levels, which in turn depend on climatic factors. Thus, for example, it has been shown that the duration of the development of *Macrocentrus grandii* Goidanich, a polyembryonic parasite of the larvae of *O. nubilalis*, was shorter when temperatures were high, temperature having an appreciable influence on the development of the parasite, both inside and outside the host. Furthermore, the number of parasites which emerged was greater at 20-25°C and the parasites' ability to reach pupation successfully was affected significantly.
by temperature, the optimum being 25°C. At lower temperatures (15-20°C) the host-parasite relation is altered because of abnormalities in the pupal development (Dittrick & Chiang, 1982).

When parasites are used for fighting the pest by means of biological control, their effectiveness depends on climatic factors. Thus in West Germany the number of *Trichogramma evanescens* (Westw.) released for effective control of the pest depends on climatic conditions (Neuffer, 1981; Hassan, 1981). In France, Voegele (1981) recommends in the biological control of *O. nubilalis* by means of *Trichogramma* that in each region the species or race should be chosen which is most suited to the local climatic conditions, as each one is able to tolerate different extremes of temperature and humidity. In Iowa (USA) it has been shown that the parasite *Nosema pyraustae* most effectively reduces the larval populations of *O. nubilalis* when certain weather conditions prevail (Pierce, 1981).

**Action involving the effectiveness of treatments**

The need for chemical applications to control the pest depends on its population level, which has been shown to be dependent on climatic factors. Thus, in years when the climatic conditions are unfavourable its population level may be lower than the economic threshold for treatment. For example, in 1976 in West Germany, the spring drought and other unfavourable factors considerably reduced the pest populations and the necessity for control measures was doubtful (Stein, 1978). Also, a knowledge of the climatic factors is essential to follow the pest's biological cycle or phenology, so determining the most suitable time for applying control measures, and reducing the latter to a minimum (Suss, 1978).

Additionally the climatic conditions at and following, the time of the chemical treatment have a considerable influence on its effectiveness. The World Meteorological Organization (WMO, 1981) summarized the conditions required at the time of application according to the type of treatment, to produce some general guidelines (Table 3.3).

The form of pesticide used may demand a more restricted range of temperature than that given in the Table. For example, pesticides are more active at high temperatures, but their persistence is then less because they are broken down more rapidly. Accordingly, the lower threshold for effective use of organophosphorous insecticides is around 15°C.

Rainfall is very important because of its washing action on applied insecticides, although the effect depends on the type of rainfall, the nature of the product, and so on. As a guide, rainfall of 10 mm or so is enough to necessitate a renewed treatment, except in the case of certain systemic products which may partly overcome this washing effect.

3.2.2.2.9 The general action of climate: modelling

As for the majority of insect pests, the action of climatic factors on *O. nubilalis* is important both from a quantitative point of view (population levels) and qualitative or phenological point of view (evolution of the biological cycle). A knowledge of the numerical relations which link the action of climatic parameters with biological parameters allows the construction of models of the pest's development: the majority of these
**TABLE 3.3**

Meteorological conditions suitable for insecticide application

<table>
<thead>
<tr>
<th>Meteorological factor</th>
<th>Spraying</th>
<th>Dusting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ground</td>
<td>Air</td>
</tr>
<tr>
<td>Wind ((\text{m s}^{-1}))</td>
<td>0 - 8</td>
<td>1 - 4</td>
</tr>
<tr>
<td>Light drizzle</td>
<td>undesirable</td>
<td>undesirable</td>
</tr>
<tr>
<td>Precipitation</td>
<td>undesirable</td>
<td>undesirable</td>
</tr>
<tr>
<td>Convection</td>
<td>none to slight</td>
<td>slight</td>
</tr>
<tr>
<td>Inversion</td>
<td>desirable</td>
<td>not very desirable</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>not important (but see temperature)</td>
<td>not important (but see temperature)</td>
</tr>
<tr>
<td>Temperature (\text{\degree}C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower limit</td>
<td>about 2</td>
<td>about 2</td>
</tr>
<tr>
<td>Upper limit</td>
<td>about 32 with low RH</td>
<td>about 32 with low RH</td>
</tr>
<tr>
<td>Visibility</td>
<td>little importance</td>
<td>adequate for visual low-level flight</td>
</tr>
</tbody>
</table>
models are phenological, but in some cases approximate quantitative models may be deduced. These can be very useful for making predictions when making decisions on the action to be taken in order to control the pests.

In the case of *O. nubilalis* some of these models refer only to partial aspects of its biology, such as spring flight (McLeod, 1981) or going into diapause (Bonnemaison, 1978; Gelman and Hayes, 1980; Robin, 1980; Beck, 1982) but in other cases these models apply to the whole annual biological cycle. The classic model of this latter type was established in 1952 by Apple and uses as its basic parameter for predicting the insect’s evolution the accumulated degree-days or effective temperatures (the sum of the average daily temperature above 10°C from the beginning of the year). It is possible to use this model to make sufficiently accurate predictions of the times when the different stages are present and consequently to determine the most suitable moment for carrying out treatment. It also provides information on the appropriate time to inspect the crop in order to assess the size of infestation by *O. nubilalis* and to decide, depending on the economic threshold, whether or not to apply treatment.

Further studies have produced supplements or modifications to this general model. In Spain, Arias and Alvez (1975) consider that accumulation of the excess above 10°C of the average daily temperatures should be begun from 15 March, (a date which is slightly earlier than the beginning of the hibernating larvae’s pupation), instead of 1 January: this allowed better prediction of the advance or delay of the separate stages of development each year and, in particular, a prediction at the beginning of August of the importance of the second-generation pupation.

Recent studies which have produced detailed models include that of Coppolino (1979) in Italy, and those of Clement (1981), Anderson et al. (1982) and Brown (1982) in the USA. Brown’s model, which has a close structural relationship with the general model of development rates based on a linear function of temperature, enables predictions to be made two weeks in advance, usually with an accuracy of two days. It also provides for the inclusion of other effects of temperature, and may be extended to other species after the necessary modifications.

The application of the models to the practical situation is often found to need modification in order to adapt them to different local conditions. For example, in Hungary, Pálfy (1982) found that the first flight always begins before that which the temperature accumulation indicated, showing a need in this case to correct and adapt the corresponding temperature integral.

Attempts have also been made to provide an approximate prediction of the abundance of the pest on the basis of climatic factors in the Caucasus (USSR) by Khomyakova and Pereverzev (1980). Furthermore, these physical factors, along with economic factors, have been used in the development of a model to calculate the economic threshold of treatment for *O. nubilalis* on the maize plant in Minnesota (USA) (Chiang, 1982).
3.3 VINE PESTS: LOBESIA BOTRANA DENIS AND SCHIFF

3.3.1 Introduction

The species Lobesia botrana (Lepidoptera Tortricidae) has been selected for discussion as it is found in practically all the wine-growing areas of Europe, Asia and Africa, i.e. in approximately 90 per cent of the world's vines, Europe, in particular, having 72 per cent. It is the key pest of this crop and it is also a species which, because of its economic importance, has been studied in great depth.

3.3.2 The effect of temperature

3.3.2.1 The adult

The emergence of the adults in spring takes place when the average daily air temperature is above the threshold temperature of 10°C for between 10 and 12 days (Kostadinov, 1974). Once they have emerged, the twilight temperatures must be above 12°C for flight to take place (Russ, 1966), and mating of the adults is most effective at temperatures above 15°C.

In addition to the activity of the moth, its life span is also influenced, varying from 58 days at 13.5°C to 9 days at 30°C (Kandle and Roesler, quoted by Balachowsky, 1966), the normal life span being about 10 days.

3.3.2.2 The egg

The duration of embryo development is a function of temperature, between the limits of 9°C and 34.5°C, the minimum being 3.5 days at 30°C. At a constant humidity of 70 per cent, Gotz (quoted by Balachowsky, 1966) observed the following incubation periods. Gotz also observed that temperature and relative humidity have a combined influence on embryo mortality, which increases progressively above 22°C and below 18°C, the mortality rate increasing as the humidity falls.

<table>
<thead>
<tr>
<th>°C</th>
<th>Days</th>
<th>°C</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.5</td>
<td>4</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>29-33</td>
<td>3.5</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>24-26</td>
<td>4.5</td>
<td>15</td>
<td>14.5</td>
</tr>
<tr>
<td>22</td>
<td>5.5</td>
<td>10.9</td>
<td>40</td>
</tr>
</tbody>
</table>

Irrespective of the relative humidity, the absolute lethal temperature for the egg is between 40 and 50°C depending on exposure time; at 45°C all the eggs die in 9 minutes (Devitz, quoted by Ruiz-Castro, 1943).

3.3.2.3 The larva and pupa

The magnitude of the cumulative daily effective temperature has a considerable effect on the duration of these phases, as will be seen when studying the temperature integrals. The pupa during diapause has a high resistance to low winter temperatures; in hard winters they have not died when temperatures dropped to -20°C. However, at the end of the winter, when the
diapause has ended, they become more sensitive and although they can survive temperatures of 0°C, the fall in temperature to -7°C is lethal (Lecigne et al., 1976).

3.3.2.4 Temperature integrals (accumulated temperature)

For *Lobesia botrana* special attention is paid to calculating the temperature integrals (sum of the daily mean temperatures above a base of 10°C & sum of daily effective temperature) between the first captures in sexual traps and the appearance of the first glomerule, because that is the moment when treatment of the first generation, if necessary, must begin. Calculations in Switzerland (Schmid, 1978) gave a figure of 190 in 1976 (degree-days (°C)) and 220 in 1977. In Valencia (Spain) this integral gave values of 194 ± 17 for the three-year period 1977-1979 (Coscolla, 1980). Schmid also produced calculations for the beginning, the mid-stage and the end of the first and second flights in four successive years. The integral to 50 per cent of the first flight averaged 144, and for the second flight, 660. The average integral for the start of the first flight was only 55, and for the second flight, 520. The average integral at the end of the first flight was 230 and the second, 750.

In Valencia the temperature integrals from the 1st of January to the peak of the first flight were 252 ± 55, between the peaks of the first and second flights 487 ± 74 and between the peaks of the second and third flights, 796 ± 111 (Coscolla, 1980).

Dirimanov et al. (1964) indicated that in Bulgaria, during the period 1959-61, the temperature integrals for the development of the first and second generations, calculated from the start of sexual maturity in adults of the previous generation to the termination of pupa formation, averaged 402 and 441 degree-days respectively.

In Romania, Filip et al. (1977) indicated that before the need arose to give an opinion on whether the first generation needed to be treated, the temperature integral had to reach 120 degree-days.

In the model designed for the Toulouse region by Touzeau (1979), again taking the sum of the average daily temperatures above 10°C, incubation of the eggs required an integral of 75 (first and third generations) to 65 (second generation) while development of the larva needed integrals of 170 (first generation) and 255 (second generation). For the prepnymphs and pupa formation period integrals of the order of 130 degree-days were needed for both generations.

3.3.3 Effect of relative humidity

Relative humidity affects the life span of the adults. At a constant temperature of 18°C, the life span is as follows (Kancke and Roesslev, quoted by Balachowsky, 1966):

<table>
<thead>
<tr>
<th>R.H.%</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>60</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>30</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>
ETEOROLOGICAL ASPECTS OF PROTECTION AGAINST INSECT PESTS

Relative humidity also affects egg mortality, in relation to temperature. This influence is greatest as the limiting temperatures for the development of the insect are approached. In very hot, dry summers there can be considerable egg mortality (Coscolla, 1980).

The combined effect of temperature and relative humidity on the life of the insect is reflected in Stellwaag's ecoclimatogram, derived from laboratory experiments (Figure 3.5). The validity of this ecoclimatogram has been confirmed by recent field studies (Coscolla, 1980; Coscolla and Davila, 1983).

![Ecoclimatogram](image)

Figure 3.5 Activity of Lobesia botrana in relation to temperature and humidity

A — limit of the zone of activity of Lobesia
I — main activity and maximum laying of Lobesia

3.3.4 Effect of other factors

Rain prevents the twilight flight of adults; also they cannot lay, even if it is not raining, if the vine-leaves are wet during the hours of twilight, generally between 6pm and 8pm in France (Touzeau, 1979). Winds, once they reach a certain level, also reduce adult flying (Russo, 1966).

3.3.5 Effect of the photoperiod

In 1947 Komarova in the USSR postulated that there might be a relationship between the photoperiod and diapause for Lobesia botrana. The results obtained from various experiments (Komarova, 1954) confirmed this hypothesis: reduced periods of daylight provoked diapause in the pupa, but only when the first stages and particularly the egg stage had been subjected to conditions of reduced daylight hours. From the third larval stage onwards, the effects of reduced periods of daylight were less noticeable.

It was found that this critical period corresponded to a daylight duration of 14 hours 38 minutes, calculated between sunrise and sunset; taking into account the duration of twilight illumination, which would have a certain influence, the daylength corresponding to this critical period would be approximately 15 hours 40 minutes. Once it was realised that there was a critical period beyond which diapause was bound to occur, the irregularity of
the of the third flight in those ecologies in succeeding years was readily understood.

Komarova's experiments also show that temperature, which regulates the earliness of the adulta's appearance in spring, the duration of egg incubation and the rate of development of the larvae, is also responsible, indirectly, for the extent of diapause in the second generation pupae and consequently the size of the third generation, as the third flight may be non-existent, total or partial depending on whether laying and the development of the larvae took place before or after the critical date corresponding to the day length required for diapause.

Geoffrion (1970) attempted to confirm these results with populations of Lobesia botrana in the Loire Valley (France), by studying the percentages of diapause in eggs and larvae exposed to increasingly short periods of daylight (reducing by 3 minutes per day), and observed that between the broods at 16 hours of daylight and those at 15 hours 45 minutes of daylight, the percentage of diapause rose from zero to 100 per cent. He also noted the high degree of sensitivity of the eggs and young larvae to the photoperiod, this sensitivity decreasing as development progressed. Taking the period of twilight into account, the results agreed well with Komarova's experiments, so one can conclude that the critical photoperiod is close to 14 hours 38 minutes, calculated between sunrise and sunset, which in the Loire Valley places it about the 20th July. When the eggs were laid before this critical period, diapause would not be induced and there could be a third flight. When laying was later, diapause would be induced and a third flight would not take place. The third flight would only be partial if some laying occurred before and some after the critical point. In fact a small correction had to be made in practice for the Loire region, since the photoperiod was somewhat greater, and Geoffrion therefore placed the critical period at the beginning of July.

The date of the critical period can be determined for each wine-growing region from its latitude. By taking other factors into account, particularly the thermal integrals, the occurrence of a third, and even a fourth, flight can be anticipated.

3.3.6 Modelling

Models have been constructed showing the development over time (phenological models) of Lobesia botrana as a function of climatic parameters. The most highly developed model was that proposed by Touzeau (1979) for the Midi-Pyrenees region of France. In this model some biological parameters are fixed while others depend on maximum temperature, the extent of leaf wetting, the photoperiod and other factors, but fundamentally the model is based on the use of thermal integrals. Although in general the philosophy of the model can be regarded as valid, the parameters need to be checked and corrected in each case in order to adapt it to different regions. One example of this is the work done by Gennatas and Toussaint (1983). More recently in Czechoslovakia a model of the development cycle of Lobesia botrana has been completed, based on constant thermal integrals for each individual stage of development and the effect of the photoperiod in inducing diapause, and it has been used for predictions. The results over three years show a difference of ±3 days between the actual and the calculated time of development of the pest population (Gabel and Mocko 1984).
3.4 COTTON PESTS: PECTINOPHORA GOSSYPIELLA (SAUND.)

3.4.1 Introduction

Of the many pests which can attack cotton in various parts of the world, the "pink bollworm" (Pectinophora gossypiella) has been chosen because it is one of the most-studied pests in cotton-growing areas. It is found in the cotton-producing regions of Europe, Asia, Africa, North and South America and Australia and the islands of the Pacific. Its economic effects are considerable, and it is regarded as one of the "key pests" of cotton.

In addition, there are many studies in existence that establish the relationship between meteorological factors and the development of the pest and its control. Most of these studies have been assembled in the review by Omar (1980), which provides much of the material in the following discussion.

3.4.2 Effect of air temperature

3.4.2.1 The adult

Temperature influences the emergence of adults in spring. This is reduced when the mean temperature drops below 21.1°C (Brazzel and Martin, 1959). Bariola (1983) noted that in Arizona the sum of the effective temperatures (above 12.8°C) when 50% of the adults had emerged was 1176 and 1174 degree-days (°C) in 1980 and 1981 respectively. This suggests that accumulated temperatures can provide a consistent indication of the moment when the adults emerge.

Various authors (quoted by Omar, 1980) have found that the life span of the adults decreases as the temperature rises.

Fertility is also influenced by temperature, being highest at 25°C (and in general between 22 and 30.5°C) decreasing markedly below 18°C, 20°C or 21°C or above 31°C, 32.4°C or 35.5°C, according to different authors (El-Sayed and Abd El-Rahman, 1960; Graham et al., 1967; Noble, 1969). Egg-laying practically ceases at 15.6°C (Noble, 1969).

3.4.2.2 The egg

The duration of the incubation period for eggs depends on temperature, decreasing as the temperature rises, between 18°C and 35°C. The survival rate of the eggs also depends on temperature, being highest at 25°C and reducing noticeably above 30°C or below 22°C (El Sayed and Abd El-Rahman 1960). High temperatures (above 35°C or 40°C) may produce high egg mortality depending on the exposure time and relative humidity (Guerra and Ouye 1968).

3.4.2.3 The larva

The duration of the different larval stages diminishes as the temperature rises. Mortality is at a minimum at 25°C then increases with any rise or fall in the temperature. At 40°C there is 100% mortality (El-Sayed and Abd El-Rahman, 1960).

The lower threshold for larval development is 13°C (El Sayed and Rustom, 1960a). Although induction of diapause is basically controlled by the
CHAPTER 3

photoperiod it may be influenced by temperature (Lukefahr et al., 1964). This effect is more marked if the temperature fluctuates than if it is constant (Menaker and Gross 1965). However, investigations in the Punjab (Simwat et al., 1982) appear to show that the combination of very high temperatures and low relative humidities may cause a certain level of larval mortality during diapause.

The termination of larval diapause is also influenced by temperature. In studies at a constant temperature of 13.4°C no pupation was induced, while at 15.6°C it was initiated under certain conditions (Watson et al., 1973). A particularly favourable temperature for inducing pupation was 26°C (Metwally and Hosny, 1972). In general, one can say that the time necessary for termination of diapause diminishes as the temperature rises (El Sayed and Rustom, 1960b); however, with highly fluctuating temperatures and short, decreasing photoperiods the time required for terminating diapause increases, whilst relatively low temperatures (within certain limits) with long daylight periods shortens the necessary time (Gutierrez et al., 1981). These same authors propose a model that relates the results of studies on induction and termination of diapause thus enabling estimates to be made of its termination in spring.

Winter mortality of larvae may on occasions be due to low temperatures. Although there are recorded cases of larvae surviving in the USA at -17.8°C, rapid drops of temperature in the autumn that freeze the larvae may however cause considerable mortality; these mortality rates are much lower with periods of prior cooling (Chapman et al., 1960). Relatively low temperatures over long periods may also produce mortality, as occurred when larvae were kept in a refrigerator for a month at 3.3°C. In zones of China where temperatures reach -20°C, all the hibernating larvae were found to have died (Fu et al., 1958).

3.4.2.4 The pupa

As at other stages in the life of the insect, the duration of the pupal stage increases as the temperature drops. Although mortality is less influenced than in the other stages, it gradually reduces to zero when the temperature rises to between 16°C and 25°C, and then increases as the temperature rises further (El-Sayed and Abd El-Rahman, 1960). Temperatures of 10°C or below inhibit the emergence of adults, but when the pupae are exposed to 15.6°C for more than one day the emergence of the adults is triggered.

3.4.2.5 Remarks on the effect of air temperature

In general, the ideal air temperature for the development of the different stages of the insect is between 25 and 28°C; temperatures above or below this tend to reduce survival. Mortality is usual above 40°C. At the lower limit, they can tolerate temperatures in the vicinity of freezing for short periods provided they have previously been conditioned by cold weather; but if the low temperatures are persistent or if they are extreme, though of shorter duration, mortality may be high (Omar, 1980).

3.4.3 Effect of relative humidity

Various authors (quoted by Omar, 1980) indicate that adult life span increases as the relative humidity rises: egg hatching is also favoured
by relatively high humidity (Adkisson, 1959; El-Sayed and Abd El-Rahman, 1960).

In the cases of induction and termination of diapause, some authors suggest that its influence is minimal (El-Sayed and Rustom, 1960a) but others indicate that, under certain conditions and depending on the photo-period, high levels of humidity can promote rapid termination of the diapause and pupation (Wellso and Adkisson, 1964).

In many cases the effect of relative humidity is presented in combination with temperature. An example is larval mortality during diapause, attributed to a combination of high temperatures and low relative humidity (Simwai et al., 1982).

3.4.4 Effect of soil temperature

Temperature affects the mortality of buried larvae in the soil. Figure 3.6 shows the median lethal time in days for larvae at different temperatures (Richmond and Clark, 1965). It can be seen that as the temperature increases the time required to produce adverse effects is reduced. Additionally, these authors suggest that daily fluctuations in temperature have an adverse effect on the larvae.

![Figure 3.6 Median lethal time in days for larvae of Pectinophora gossypiella in the soil](image_url)

Henneberry et al. (1982) indicate that raising the soil surface temperature to 68°C for 10-15 seconds killed 81 per cent of larvae, while 1 to 4 minutes at 52°C had no effect on mortality. Two to 16 hours at 49°C killed 57-95 per cent of the larvae. This agrees with the observations of Chapman et al. (1960) which indicate that when the surface temperature is between 50.5 and 68.5°C mortality of diapausal larvae is high.
CHAPTER 3

The activity of buried larvae is also influenced by soil temperature. This activity increases in Spring when the soil is warm and moist (Fife and Graham, 1965). Adverse temperatures, in addition to producing mortality, retard the development of the surviving larvae (Henneberry et al., 1982).

3.4.5 Effect of rainfall and soil moisture

It has been long known that soil moisture is a key factor in controlling this pest. In 1925 Williams and Bishara had already noted that in Egypt mortality increased with soil moisture, and that few insects emerged from over-irrigated fields, thus providing a method of protecting the next season's crop. In the USA, increasing the soil moisture by irrigation during the winter is an important method of controlling the pink bollworm. Laboratory studies (Richmond and Clark, 1965; Fye, 1973) and field observations (Chapman et al., 1960; Bariola, 1983) both show that high moisture content in the soil during the winter period increases the mortality of larvae and pupae in the soil to a marked degree. These high levels of moisture may be due to irrigation or to heavy rainfall. In Arizona, for example, winter irrigation may reduce the survival of larvae in the diapause by 50 per cent (Bariola, 1983).

In contrast, the spring emergence of buried insects may be favoured by high soil moisture. First of all, it affects the survival rate, which was doubted by Chapman et al. (1960) by irrigation in spring. Other authors, while suggesting that soil moisture in spring has little influence on the survival rate, indicate that adults emerging from very dry soils are frequently weak and malformed (Fife and Graham, 1966). Secondly, and all authors are in agreement on this (Fife, 1961; Clayton et al., 1982; Henneberry and Clayton, 1983; Bariola, 1983), the emergence of adults is favoured by soil moisture. Thus Henneberry and Clayton (1983) note that the larvae become active earlier in moist soil (11-15 per cent moisture) than in dry soil (2 per cent moisture) and consequently they also pupate earlier and emerge as adults earlier. Usually, the emergence of the adults comes between 2 and 3 weeks after a significant Spring rainfall (minimum of 12 mm, though sometimes at least twice this quantity seems to be required), this period becoming shorter with increasing temperature.

In general it can be said that moist winters reduce survival while moist springs favour pupation. It is also reported in China that rainfall or moist conditions favour laying, although excessive rain may have an adverse effect (Chu, 1959).

3.4.6 Effect of wind

The wind may assist the dispersion of insects, some of them travelling a long way (distances of 270 to 400 km have been noted in the USA), especially since they can easily be lifted to a height of 900 metres (Glick, 1967). However, it can also interfere with their normal activity on the ground. Captures in light traps were greater when the wind speed did not exceed 5 km/h. This value can be taken as a threshold beyond which the insects have difficulty in regulating their flight (Glick and Hollingsworth, 1956).
3.4.7 Effect of the photoperiod

It has been known for some time that in different parts of the world larvae enter diapause at approximately the same time at any given latitude, which suggests that the photoperiod has some effect on the induction of the diapause. Adkisson et al. (1963) noted that day lengths of 13 hours or less induced diapause, while day lengths of 13.25 hours or more did not. They also indicated that diet has an effect in inducing diapause. Lukefahr et al. (1964) found, in addition to the secondary influence of temperature on this induction, that photoperiods progressively increasing from 12 to 16 hours or constant photoperiods of 14 hours favour the development of non-diapausal larvae, while decreasing photoperiods induce the larvae to enter diapause. These same authors note that since diapause in the insect is basically determined by the photoperiod, this means that the photoperiod largely determines the insect's seasonal distribution and abundance. Thus diapause is rare in the equatorial region between 10°N and 10°S, given that the day length is almost constant throughout the year at approximately 14 hours, including the pre-dawn period and twilight. Moving further from the equator, diapause begins as the day length changes. At latitudes beyond 32°N the number of generations is substantially less.

The photoperiod, in conjunction with fluctuations in temperature, also has an influence on the termination of diapause. Watson et al. (1973) indicated that less pupation occurred in photoperiods of 14 hours than of 10 hours, this being more evident at a constant low temperature than with a fluctuating low temperature. It has recently been shown that long daylight durations and not very high temperatures (within certain limits) promote termination of diapause (Gutierrez et al., 1981).

3.4.8 Final remarks

Clearly, meteorological factors play an important role both in the biology and the control of the pink bollworm. In particular photoperiod and, to a secondary extent, temperature, determine diapause, and consequently are important factors in the geographical and general distribution of this pest. Temperature and soil moisture may also be useful for predicting the emergence of the adults in spring, and for predicting the need for control measures. Wind may be an important factor in spread.

Attempts have been made to find quantitative relationships between climatic factors (maximum and minimum temperatures, relative humidity in the morning and afternoon, hours of daylight, intensity and number of rainfalls, etc.) and the incidence of the pest by means of multiple regression studies. Thus, for example, under specific conditions a temperature rise of not more than 1°C can produce a 4 per cent increase in the incidence of the pest, while an additional day's rain at a certain time could reduce the amount of damage by 4 per cent (Balasobramanion, 1981).

During the most productive period of the crop in India (September - October) the most favourable conditions for rapid multiplication of the pest are warm but not excessively high temperatures (averaging around 28°C), with a relative humidity of 65-85 per cent, cloud, and frequent, light rainfall (Katiyar, 1982).
Chapter 3

Particular control measures which are partly of agro-meteorological origin may be very useful. For example, early harvesting of a crop may be important in reducing the hibernating population; it therefore becomes important to select a suitable planting date, on the basis of microclimatic and phenological studies of the crop and the pest, and possibly use chemical defoliants to bring forward harvesting to before photoperiod-induced diapause. Using these methods population reductions of up to 85 per cent have been achieved (Rice, quoted by Omar, 1980). Winter irrigation by increasing the soil moisture content can also considerably increase larval mortality.

Meteorological data (together with other biological and phenological data) are clearly essential for predicting the development and numbers of the pest, and consequently for adopting the most appropriate control strategies. However, in spite of the importance of agro-meteorological factors in the epidemiology and control of the pest, additional studies are still required to fill the gaps in our knowledge of certain important points as identified by Omar (1980). In particular further statistical and agro-meteorological studies are required before completely adequate models can be developed to predict both the times and the severity of attacks on the basis of meteorological data, and data on the crop and pest.

3.5 Storage Pests of Wheat and Other Cereals

3.5.1 Introduction

World food requirements demand a continuing effort to increase agricultural productivity and minimise losses following harvesting, the latter also because there is now a tendency to establish national and international buffer stocks of foodstuffs to provide protection against fluctuations in production.

This system of marketing and storage suffers from external attacks by pests of various kinds, amongst the most important of which is that due to the activity of insects (Coleoptera and Lepidoptera in particular) which according to FAO estimates are responsible for losses in stored cereals and their products of more than 10 per cent.

3.5.2 Storage Pests

It is well known that losses due to these insect pests vary in size because the insects are subject to environmental factors such as humidity, temperature, light levels, etc. that affect their development. For a long time the role of humidity was ignored in studies of storage pests, and mean temperature was the variable employed. More recent studies have included monitoring the natural growth of the population over periods of up to weeks or months, taking into account the influence of the relative humidity of the atmosphere, threshold temperatures, water content of the grain, etc.

As indicated earlier, the insects discussed here belong to two orders, namely:

- Coleoptera
  
  Sitophilus (Calandra) granarius (L.)
  Sitophilus (Calandra) oryzae (L.)
  Tribolium confusum (Duv.)
### TABLE 3.4

**World distribution of storage pests**

+ Major importance  
X Moderate importance  
- Negligible or nil

<table>
<thead>
<tr>
<th>PEST</th>
<th>PRODUCT ATTACKED</th>
<th>North America</th>
<th>South America</th>
<th>Europe</th>
<th>North Africa</th>
<th>South Africa</th>
<th>West Asia</th>
<th>East Asia</th>
<th>Oceania</th>
</tr>
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<tbody>
<tr>
<td>S. granarius</td>
<td>Cereals-wheat</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>X</td>
<td>+</td>
<td>+</td>
<td>X</td>
<td>+</td>
</tr>
<tr>
<td>S. oryzae</td>
<td>Cereals-rice</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>X</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>R. dominica</td>
<td>Cereals</td>
<td>+</td>
<td>+</td>
<td>X</td>
<td>+</td>
<td>X</td>
<td>X</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>T. granaria</td>
<td>Cereal prods</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>+</td>
<td>X</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>T. confusum</td>
<td>Cereal prods</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>+</td>
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<tr>
<td>O. surinamensis</td>
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<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>X</td>
<td>X</td>
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<tr>
<td>C. ferrugineus</td>
<td>Cereals</td>
<td>+</td>
<td>X</td>
<td>+</td>
<td>X</td>
<td>X</td>
<td>X</td>
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</tr>
<tr>
<td>C. pusillus</td>
<td>Cereals</td>
<td>+</td>
<td>X</td>
<td>+</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>X</td>
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<tr>
<td>T. mauritanicus</td>
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<td>+</td>
<td>X</td>
<td>+</td>
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<tr>
<td>P. interpunctella</td>
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<td>-</td>
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<tr>
<td>S. cerealella</td>
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<tr>
<td>E. Kuehniella</td>
<td>Cereal flours</td>
<td>-</td>
<td>X</td>
<td>X</td>
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Table 3.5 Influence of environmental factors on Coleoptera and Lepidoptera storage pests

<table>
<thead>
<tr>
<th></th>
<th>Sitophilus granarius (L.)</th>
<th>Sitophilus oryzae (L.)</th>
<th>Tribolium confusum (Duv.)</th>
<th>Cryptolestes ferrugineus (Steph.)</th>
<th>Cryptolestes pusillus (Schönbr.)</th>
<th>Tenebroides mauritanicus (L.)</th>
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</thead>
<tbody>
<tr>
<td><strong>Development</strong></td>
<td>Grain weevil</td>
<td>Rice weevil</td>
<td>Flour beetle</td>
<td>Flat grain beetle?</td>
<td>Grain beetle</td>
<td>Caddle</td>
</tr>
<tr>
<td><strong>thresholds</strong></td>
<td>(a) Min 15°C, RH 50%</td>
<td>(a) Min 15°C, RH 50%</td>
<td>(a) Min 22.5°C at 70%</td>
<td>(a) Min 20°C at 50%</td>
<td>(a) Min 7.5°C at 50%</td>
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<tr>
<td></td>
<td>grain moisture content 14%</td>
<td>grain moisture content 14%</td>
<td>Max 35°C at 70%</td>
<td>RH</td>
<td>Max 37.5°C at 70%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max 32°C, RH 10%</td>
<td>Max 32°C, RH 10%</td>
<td>Max 35°C at 70%</td>
<td>RH</td>
<td>Max 35°C at 50%</td>
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<tr>
<td><strong>Optimum</strong></td>
<td>25°C, RH 72%</td>
<td>28°C, RH 70%</td>
<td>32°C, RH 70%</td>
<td>35°C, RH 70%</td>
<td>37.5°C at 80% RH</td>
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<tr>
<td><strong>development</strong></td>
<td>15 days at 7°C, 3°C, 3°C</td>
<td>5°C, 6°C</td>
<td>3 days at 3°C, 3°C, 3°C</td>
<td>death occurs in 24 days,</td>
<td>No development whatsoever</td>
<td>Adults survive 7 months</td>
</tr>
<tr>
<td></td>
<td>not more than 5 hours</td>
<td>and 3°C, 3°C, 3°C,</td>
<td>at 7°C, 5°C, 5°C</td>
<td>death occurs in 24 days</td>
<td>No development whatsoever</td>
<td>at 5°C and 5°C, 5°C, 5°C</td>
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<tr>
<td><strong>Survival in</strong></td>
<td>at 15°C, and 50% RH</td>
<td>and 3°C, 3°C, 3°C,</td>
<td>at 7°C, 5°C, 5°C</td>
<td>death occurs in 24 days</td>
<td>No development whatsoever</td>
<td>Adults survive 7 months</td>
</tr>
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<td><strong>hostile conditions</strong></td>
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<td>No development whatsoever</td>
<td>Adults survive 7 months</td>
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<td><strong>Life cycle</strong></td>
<td>24 days at 30°C,</td>
<td>35°C, RH 70%</td>
<td>32°C, RH 70%</td>
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<td></td>
<td>24°C, RH 70%</td>
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<td><strong>Multiplies</strong></td>
<td>Under ideal conditions</td>
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<tr>
<td></td>
<td>population increases</td>
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<tr>
<td></td>
<td>15 fold in 25 days</td>
<td>15 fold in 25 days</td>
<td>15 fold in 25 days</td>
<td>15 fold in 25 days</td>
<td>15 fold in 25 days</td>
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<tr>
<td><strong>Lifespan of</strong></td>
<td>At 25°C and 70% RH</td>
<td>At 25°C and 70% RH</td>
<td>At 25°C and 70% RH</td>
<td>At 25°C and 70% RH</td>
<td>At 25°C and 70% RH</td>
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<tr>
<td><strong>adults</strong></td>
<td>Adult survives for 6 months</td>
<td>Adult survives for 6 months</td>
<td>Adult survives for 6 months</td>
<td>Adult survives for 6 months</td>
<td>Adult survives for 6 months</td>
<td>Adult survives for 6 months</td>
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<tr>
<td><strong>Influence of</strong></td>
<td>More sensitive to carbon</td>
<td>More sensitive to</td>
<td>More sensitive to</td>
<td>When breeding, more</td>
<td>More sensitive to</td>
<td>More sensitive to</td>
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<td><strong>temp and</strong></td>
<td>dioxide than at 20°C</td>
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<td><strong>RH on</strong></td>
<td>than at 20°C</td>
<td>at 20°C than at 20°C</td>
<td>at 20°C than at 20°C</td>
<td>dioxide at 20°C than</td>
<td>dioxide at 20°C than</td>
<td>dioxide at 20°C than</td>
</tr>
<tr>
<td><strong>treatments</strong></td>
<td>More sensitive to</td>
<td>More sensitive to</td>
<td>More sensitive to</td>
<td>When breeding, more</td>
<td>More sensitive to</td>
<td>More sensitive to</td>
</tr>
<tr>
<td></td>
<td>carbon dioxide at 20°C</td>
<td>carbon dioxide at</td>
<td>carbon dioxide at</td>
<td>susceptible to carbon</td>
<td>carbon dioxide at</td>
<td>carbon dioxide at</td>
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<td></td>
<td>than at 20°C</td>
<td>20°C than at 20°C</td>
<td>20°C than at 20°C</td>
<td>dioxide at 20°C than</td>
<td>dioxide at 20°C than</td>
<td>dioxide at 20°C than</td>
</tr>
<tr>
<td><strong>Effect of light</strong></td>
<td>Negative phototropism</td>
<td>Negative phototropism</td>
<td>Negative phototropism</td>
<td>Negative phototropism</td>
<td>Negative phototropism</td>
<td>Negative phototropism</td>
</tr>
<tr>
<td>Development thresholds</td>
<td>Trogaderma granarium (Everts) Kharpa beetle</td>
<td>Rhypopertha dominica (F) Lesser grain borer</td>
<td>Ephesia kuehniella (Zell.) Flour moth</td>
<td>Plodia interpunctella (Hb) Indian flour moth</td>
<td>Sitotroga cerealella (Ol.) Angoumois grain moth</td>
<td></td>
</tr>
<tr>
<td>------------------------</td>
<td>--------------------------------------------</td>
<td>-------------------------------------------</td>
<td>------------------------------------------</td>
<td>---------------------------------------------</td>
<td>-----------------------------------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(a) Min 22-25 °C at 73% RH</td>
<td>(a) Min 21 °C, regardless of humidity</td>
<td>(a) Min 10 °C</td>
<td>(a) Min 15 °C and 75% RH</td>
<td>(a) Min 15 °C and 75% RH</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(b) Max 40-42 °C at 75% RH</td>
<td>(b) Max 38 °C at 40-70% RH</td>
<td>(b) Max 35 °C</td>
<td>(b) Max 37 °C and 75% RH</td>
<td>(b) Max 35 °C and 75% RH</td>
<td></td>
</tr>
<tr>
<td>Optimum development</td>
<td>35 °C at 73% RH</td>
<td>34 °C and 70% RH</td>
<td>28-30 °C and 50-60% RH</td>
<td>30 °C and 70% RH</td>
<td>35 °C at 75% RH</td>
<td></td>
</tr>
<tr>
<td>Survival in</td>
<td>Development in grains with low moisture</td>
<td>Resistant to heat and lack of moisture</td>
<td>5-6 hours at 55-90 °C</td>
<td>No development whatever the temp if RH &lt; 30%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hostile conditions</td>
<td>content 7-7% survive when RH does not exceed 2% and temp is 25-40 °C. Larval mortality is more than 50%. In most cases when RH is very low, mortality falls to 9% if temp is 35 °C with RH of 20%. At 35 °C the larvae enter diapause and it is believed they cause no damage when mean temp does not exceed 20 °C</td>
<td>develop in grain with 9% water content at 20 °C and 20% RH</td>
<td></td>
<td>21 days at 30 °C. At 30 °C and 70% RH, 20 days. Egg, at 10 °C, 10 days at 21 °C, 8 days at 25 °C, 4 days at 32 °C, 1 day at 17 °C, 20 days at 30 °C, 8 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Growth cycle</td>
<td>At 35 °C and 73% RH, 24 days</td>
<td>At 34 °C and 70% RH, 20 days</td>
<td>At 30 °C and 70% RH, 20 days. Egg, at 10 °C, 10 days at 21 °C, 8 days at 25 °C, 4 days at 32 °C, 1 day at 17 °C, 20 days at 30 °C, 8 days</td>
<td>At 15 °C and 75% RH, 80 days. At 20 °C and 75% RH, 35 days. Egg, at 10 °C, 10 days at 15 °C, 4 days at 30 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiplication</td>
<td>Under ideal conditions population increases by 12.5 times in 28 days</td>
<td>Under ideal conditions (34 °C and 70% RH) population increases 26-fold in 28 days</td>
<td>Under ideal conditions population increases 50-fold in 28 days</td>
<td>Under ideal conditions population increases 50-fold in 28 days</td>
<td>Under ideal conditions population increases 50-fold in 28 days</td>
<td></td>
</tr>
<tr>
<td>Lifespan of</td>
<td>At 25 °C and 70% RH, adults live for 2 weeks</td>
<td>Adults live for 4 months at 32 °C and 70% RH</td>
<td>Adults live for 1-3 weeks</td>
<td>Adults live for 1-3 weeks</td>
<td>Adults live 1 month at 12 °C, or 2 weeks at 25 °C, with 75% RH</td>
<td></td>
</tr>
<tr>
<td>adults</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Influence of</td>
<td>Effect of temp and RH on treatments: A positive correlation is observed between temp and toxicity in the range 10-35 °C for carbon disulphide, ethylene diamine, etc. Following treatment sensitivity to pyrethrins increases with temp</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>temp and RH on</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>treatments</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Effect of light</td>
<td></td>
<td></td>
<td></td>
<td>Negative phototropism</td>
<td>Negative phototropism</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 3

Cryptolestes ferrugineus (Steph.)
Cryptolestes pusillus (Schonh.)
Trogoderma granarium Everts
Tenembroides mauritanicus (L.)
Rhyzoperthum dominica (F.)

- Lepidoptera

Ephestia kuehniella (Zell.)
Plodia interpunctella (Hb.)
Sitotroga cerealella (Ol.)

Given the nature of trade in cereal products, most of the species listed above are now cosmopolitan. Nevertheless, Table 3.4 is given showing the world distribution of each pest and the extent of its attacks. The point should be made that in the case of stored crops we can attempt to regulate the environmental conditions - temperature, relative humidity, grain moisture content, lighting, etc. - which means that an understanding of the influence of these factors on the insects is particularly valuable. Table 3.5 summarizes some of these responses for the pests already described.

3.6 CONCLUDING REMARKS

The examples given show clearly the existence of a close relationship between weather conditions and crop health. However, it must be remembered that mathematical relationships constitute an abstract and imperfect representation of the real world, and in the words of Sir Napier Shaw any theory of the course of events in nature is necessarily based on some process of simplification and to some extent is therefore a fairy tale (quoted by Odum '71).

In effect, we must take account of the fact that the biological processes being considered are very complex due to the large number of factors involved, which means that each case has its own specific peculiarities. It is for this reason that our existing, established knowledge is subject to continuous revision as the problems are studied more fully and deeply. Nevertheless, our present knowledge on this subject, whatever its limitations, can be used by agricultural advisers to provide a useful service to growers in their battle against pests and diseases in their crops. Such information, based on meteorological data in combination with phenological and biological data, can alert the grower to the most appropriate means of defence.

As our knowledge of these relationships increases, it will be possible to construct ever more accurate models, which will enable us to simulate the development of pathogens as a function of the progress of meteorological events. This will also enable us to make predictions some days in advance, on the basis of our ability to forecast the values of certain meteorological factors. Eventually it is to be hoped that all crop protection operations will be planned on a rational basis, using all available forms of meteorological information.
Future lines of work in this field should be aimed at:

- Improving our understanding of existing data on major pests and diseases and their response to the environment by carrying out further studies to establish relationships with greater precision;

- Acquiring new knowledge of other, less frequently studied pests and diseases by means of appropriate experimental investigations;

- Undertaking the testing and adaptation of the proposed equations and graphs to suit the particular conditions of each region;

- Encouraging the use and adaptation of modern technologies (remote sensing, radar, computers, etc.) to deal most effectively with meteorological data for agricultural purposes.

The ultimate objective is the construction of the most accurate models possible of the development of plant pests and diseases. If this could be combined with an increased accuracy in weather forecasting, the result would be a major step towards combating the hazards to our crops in a rational manner.
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REFERENCES


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CHAPTER 4

LOCUSTS AND OTHER INSECT PESTS WITH LONG-RANGE MIGRATION

4.1 INTRODUCTION

There are a number of insect pests of major economic importance which not only cause local damage in their breeding habitats but also migrate long distances under the influence of airflows in the lower atmosphere. Some of the pests travel in swarms, occasionally of enormous size, causing severe crop damage in places which may be hundreds of kilometres from their birthplace.

The breeding success of such insects, and the pattern of their subsequent migration are generally linked closely with meteorological factors: forecasting schemes that use comprehensive weather information have therefore proved very valuable in operations to control these pests.

4.2 LOCUSTS

These are species of grasshoppers which have developed the capacity to form dense assemblies of nymphs (hopper bands) or adults (swarms). There are about fifteen species, in the warmer parts of the world. The desert locust (Schistocerca gregaria) has been the subject of the most study. During recession periods, and like most other locust species, it breeds in relatively restricted areas with little or no swarming. At times of plague it has been found at places within an area of around $3 \times 10^6\ km^2$ in Africa and south-west Asia (Figure 4.1, Pedgley 1982). Studies have shown that actively flying desert locusts eat approximately their own weight of vegetation daily, and a heavy locust invasion can involve daily feeding rates of around $10^5$ tonnes (Rainey, 1963). Most of the food is provided by natural vegetation but nonetheless crop losses from attack by a swarm would be very large. Rainey (1963) reports that a particular swarm originating in the northern Arabian peninsula moved to Niger, a distance of 3500 km in a month, and states that

![Figure 4.1 Invasion area of swarms of the desert locust (Schistocerca gregaria) during plagues and recessions (Pedgley, 1982)](image-url)
such distances of migration are not uncommon. The last major plague of this species ceased in the early 1960s, and since then outbreaks have been relatively minor as a result of improved methods of monitoring and control.

Another important locust species is the migratory locust (Locusta migratoria): in the plague years of 1928 to 1941 a sub-species of this pest infested most of Africa south of the Sahara (Batten, 1967, 1972) (Figure 4.2).

![Figure 4.2 Outbreak and invasion areas of the African migratory locust (Locusta migratoria migratorioides) for the 1928-41 plague (after Batten, 1967)](image)

The red locust (Nomadacris septemfasciata) has reached epidemic proportions in Africa, chiefly south of the equator, during the period of plague from 1930 to 1944 (Symmons, 1978) (Figure 4.3).

The Australian plague locust (Chortoicetes terminifera) occurs widely on that continent, and it forms swarms in some years.

4.2.1 Factors in locust activity and control

Locust control strategies have improved considerably from those used fifty years ago when methods aimed chiefly at reducing crop damage after the locusts had already reached cultivated areas. Present strategies for
all species involve monitoring populations in the relatively restricted seasonal breeding areas and mounting control campaigns if populations begin to form swarms. The success of this technique is such that there has been no new plague in Africa since the desert locust plague that began in 1949, and there has been relatively little crop damage since that plague ended in 1962. However, the monitoring programme is not without difficulties, and breeding is not always detected in time to prevent some swarms forming, though fortunately, in recent years, without major plagues developing.

4.2.1.1 Breeding areas

The main breeding areas of the desert locust have been described in detail in the Desert Locust Forecasting Manual (COPR, 1981). Many of these areas are remote from populated regions (e.g., in western Sahara and northern Mauritania, in wadis draining the southern Sahara uplands in Mali, Niger and Chad, the interior of south west Arabia and the Indo-Pakistan border), and so breeding can occur which might be undetected, or if detected, only partially controlled. The use of remote sensing imagery has recently provided a valuable technique for assessing the suitability of these remote or inaccessible areas for breeding (see below).

The two major areas of outbreak for the african migratory locust are in the delta region of the river Niger in Mali, and the Lake Chad basin. Red locusts breed chiefly in ten outbreak areas extending from northern Tanzania to southern Mozambique.

4.2.1.2 Breeding requirements

In the case of the desert locust, egg-laying insects seek warm open sites, with a soft, dry, sandy surface preferred to a moist compact one.
However, egg laying only takes place when there is a moist layer between 5 and 15 cm depth (Popov 1958). Popov suggested that a rainfall of 15-20 mm, 1 to 2 days before laying, provided the best conditions: larger amounts would be needed if the insects arrived several days after the rainfall.

After laying, the eggs need to absorb approximately their own weight of water before hatching is possible (Hunter-Jones, 1964). Rate of egg development is a function of soil temperature. However, soil temperature data are seldom available near the laying sites (except perhaps via remote sensing) and mean daily air temperature is a useful substitute. Symmons et al. (1973, 1974) found that the incubation period decreased from 65 days to 10 days when air temperature increased from 12 to 34°C.

Rate of development of hoppers after hatching is also dependent on temperature, with last moult (at end of the fifth instar stage usually) reached in about 50 days at an air temperature of 24°C, and 25 days at 32°C (Wardhaugh et al., 1969).

Hoppers eat approximately their own weight of vegetation each day (Davey, 1954) and so require an ample food supply in order to develop. An essential meteorological requirement is therefore rainfall. Some feeding on perennial plants takes place, but a great deal of the required food often comes from ephemeral plants that germinate freely following seasonal rains of 25 mm or more.

Information on the breeding requirements of other species is generally sparser, but broadly similar requirements for rainfall, and responses to temperature are likely (Duranton et al. 1982).

4.2.1.3 Migration

Locust swarms usually fly only by day. Studies on the desert locust in particular have shown all directions of flying in individual swarms but those insects at heights above a few hundred metres more often move downwind, sometimes reaching the top of the boundary layer while doing so. Locusts turn back on reaching the edge of the swarm, and higher flying insects return to the surface layers, leading to overall movement of the swarm in the downwind direction (Pedgley, 1982). Migration continues until suitable breeding grounds and sexual maturity are reached: comprehensive details are provided in COPR (1981).

There is evidence of downwind movements of swarms of species other than the desert locust, although daily migration distance may be only around 10 km a day, compared to 50-100 km for desert locusts in warm, sunny weather (Pedgley 1982).

4.2.1.4 Meteorological requirements in locust control

Reviews of these requirements are provided by Hemming (1980) and COPR (1981). Breeding success of locusts is largely determined by rainfall since temperature is not a first-order limiting factor. Movement of locusts after they leave the breeding grounds is controlled principally by wind velocities in the atmospheric boundary layer. Coincidence of rainfall at
potential breeding grounds along the migration track with the passage of sexually mature swarms allows further successful breeding and the chance of further swarm development. The costs of controlling outbreaks that develop in this way can be extremely high. Thus Hemming (1980) described the enormous quantities of liquid insecticide (220,000 litres before dilution) and BHC dust (130 tonnes) used in Pakistan in 1978 in order to control outbreaks of locusts that originated in Africa in 1977, in areas of political instability that had prevented adequate control measures early in the epidemic.

Even without the loss of data through internal disorder, the limited raingauge data from the main breeding areas of locusts are often insufficient to give warning of the build-up of locust populations soon enough for relatively cheap control methods to be effective. Fortunately, satellite imagery is able to provide information valuable in locust control. The potential of satellites for this purpose was demonstrated in the early 1970s in an experiment using Landsat data to detect surface colour changes as vegetation developed following rainfall, and hence to identify areas within which successful breeding was occurring (Pedgley, 1974). Landsat is not suitable for operational monitoring because of its very high resolution and its 18-day interval between successive scans of the same area, but data from other satellites, especially polar orbiting ones and Meteosat, are now used in the operational locust monitoring scheme run under the auspices of the FAO. These satellites provide information not only on vegetation development following rainfall (through surface colour change), but also on surface temperature which can be used to identify areas of rainfall through the surface cooling that occurs as soil moisture evaporates: additionally they obtain data on cloud top temperature which may be used to estimate the height of convective storms, and from this and the observed lifetime of the storms an indication of the associated rainfall amount. This information, along with observations from the conventional surface-based meteorological network, and boundary-layer winds from radar- and theodolite-tracked pilot balloons, permits the successful operation of current locust monitoring and control schemes.

4.3 OTHER INSECT PESTS WITH LONG RANGE MIGRATION

Favourable winds occasionally carry small numbers of insect pests very large distances: for example, Hurst (1969) describes the arrival in the UK of a locust which backtracking indicated had come from Morocco. However, many insect pests are regularly carried from their region of origin in sufficient numbers to cause significant crop damage in areas many hundreds of kilometres away. A distinction needs to be drawn between migrations where the numbers arriving are large enough to cause an immediate threat to crops, and migrations of much smaller numbers of insects which, while unlikely to cause much damage, provide a breeding stock that, in the case of aphids, for example, can multiply quickly and reach economically damaging proportions. Operational monitoring of lower tropospheric airflow (as a minimum) is necessary in either case in order to anticipate arrival of the pests, and is essential for the first kind of migration if timely control measures are to be taken.

A variety of pests cause crop damage in regions where they are often unable to overwinter due to low temperatures. Their arrival usually coincides with warm southerly winds. Examples have been given by Wiktelius
(1977) for aphids reaching Sweden during the summer; in the USA Kaster and Showers (1982), Smelser et al. (1985) and USDA (1985) describe migrations earlier in the year to the Midwest from further south by the black cutworm (Agrotis ipsilon Hufnagel) which damages seedling maize, and Wolf et al. (1985) discuss similar migrations of the green cloverworm (Plathypena scabra (F)), an occasional pest of alfalfa and soybeans. Even when overwintering is possible, such migrations may bring in pests substantially earlier in the year than the date of maturity of the indigenous population.

Summaries of many other studies of long range migration of important insect pests have been provided by Johnson (1969) and Pedgley (1982). Of particular interest is the annual pattern of movement over China of the oriental armyworm (Pseudaletia separata (Walk.)), a serious pest in parts of Asia and Australia, the Pacific Islands and New Zealand. Evidence presented by Li et al. (1964) suggests that there are five main outbreak areas in eastern China, coinciding with successive generations of the pest moving from area to area on favourable winds in the lower troposphere (Fig 4.4). The first generation, after damaging spring wheat in the south in late winter moves north in the spring, while fourth or fifth generations return south in the autumn to damage rice and to overwinter.

![Diagram](image-url)

Figure 4.4 Main outbreak areas and direction of seasonal migrations of five generations of the oriental armyworm (Pseudaletia separata) in Eastern China. Heavy lines show major routes of migration and broken lines show their possible extensions (Johnson, 1969, after Li et al., 1964)
Clearly the necessary meteorological factor in all cases of very long migration is a favourable wind direction, but temperature and rainfall may also have a part to play. Temperature, for example, will inhibit successful migration into non-overwintering areas until it rises above the threshold appropriate to the pest, and may also influence the size of population in the source region at the time when migration first becomes possible. Rainfall over large areas may ground the insects and prevent completion of the normal pattern of migration.


Johnson, C.G., 1969: Migration and Dispersal of Insects by Flight. Methuen, London. 763 pp


CHAPTER 5

METEOROLOGICAL ASPECTS OF WEEDS

5.1 INTRODUCTION

Weeds reduce agricultural productivity in a number of ways (Furtick, 1978; BCPC, 1982). Their most direct influence comes from competition for available nutrients, soil moisture and light. They may also act as temporary hosts for pests and diseases, providing a "green bridge" that allows these organisms to pass through a succession of crops. Heavy weed infestations can interfere with the harvest operation, and contamination of the harvested crop by weed seeds may reduce its value. Many weed seeds remain viable in the soil for a number of years and so inadequate weed control can lead to a progressive build-up of weeds from year to year.

Weeds are characterized by their great diversity, and especially by their ability to compete successfully with cultivated crops. If unchecked they can cause extremely high losses (Table 5.1). Loss of crop yield increases rapidly if weeding is delayed (Table 5.2): this has important implications for subsistence farmers growing food rather than cash crops and who do not have sufficient income to provide mechanized or chemical methods of weed control; here the need for frequent, timely weeding often makes the proportion of time spent weeding so large that it limits to little more than one hectare the maximum area of land which can be usefully cultivated by a family. However, the complete destruction of weeds is not necessarily desirable. For example, Well (1982) found that in central Malawi where rainfall is around 1000 mm during the maize-growing season, losses of soil due to erosion were reduced by two-thirds when plots were left unweeded.

TABLE 5.1

Average percentage crop losses due to uncontrolled weed growth (Moody and Ezumah, 1974)

<table>
<thead>
<tr>
<th></th>
<th>Yams</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>West Indies</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>Nigeria</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Côte Ivoire</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>Cassava</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fiji</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>Venezuela</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>Nigeria</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>Colombia</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>Sweet Potatoes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>West Indies</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>Nigeria</td>
<td>91</td>
</tr>
</tbody>
</table>
CHAPTER 5

TABLE 5.2
Critical periods of weed competition in beans and maize in Mexico (Nieto et al., 1968)

<table>
<thead>
<tr>
<th>Duration of weed competition</th>
<th>Percentage yield reduction caused by weeds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beans</td>
</tr>
<tr>
<td>10 days</td>
<td>4</td>
</tr>
<tr>
<td>20 days</td>
<td>22</td>
</tr>
<tr>
<td>30 days</td>
<td>52</td>
</tr>
<tr>
<td>40 days</td>
<td>82</td>
</tr>
</tbody>
</table>

The great majority of weed problems are associated with about 200 species, in some 60 plant families (Holm, 1976; Holm et al., 1977): most of the weeds are annuals. Twelve families (Table 5.3) provide most of the problems: grasses and sedges make up about one-quarter of the species and Asteraceae a further one sixth. At the same time the thirteen largest food crops, more than three quarters of man’s food, are with one exception also found in these same twelve families.

TABLE 5.3
The important weed families

| Poaceae (Gramineae) | 44 species )  ) 27% )  ) |
|                    | 12   ) ) 43%  )  ) |
| Cyperaceae         | 32   ) ) ) ) |
| Asteraceae (Compositae) | 8  ) ) 68% )  ) |
| Polygonaceae       | 7 each ) ) ) ) |
| Amaranthaceae, Brassicaceae | 6 ) ) ) ) |
| Leguminosae        | 5 each ) ) ) ) |
| Convolvulaceae, Euphorbiaceae | 4 each ) ) ) ) |
The weed species in a field will clearly depend on the local climate, but also on the type of agricultural system: in intensive systems, with a small number of crops grown in rotation, the number of species is usually low (10-15), but may exceed 50 in more extensive farming with diversified crop rotations (Koch and Walter, 1983). Most of the damage, however, is usually caused by only a few of the species present.

Warm, moist climates without large seasonal variations in rainfall and day-length allow continual, rapid development of weeds, and demand vigorous control methods to reduce resulting crop losses to acceptable levels. In temperate latitudes, however, a much more varied response of the weeds is observed. Some species flower only when days are shorter than a critical length (short-day plants) while others have the opposite response (long-day plants). Other species may have no day-length response, or multiple responses (e.g. short days followed by long days): yet others may require an exposure to low temperatures (vernalization) in order to initiate flowers.

Moisture, oxygen and a suitable temperature are essential for the germination of seeds. Oxygen is rarely a limiting factor except occasionally in very wet soil conditions. Germination does not occur in very dry conditions; with adequate soil moisture it is temperature which determines whether seeds will germinate and when. Some species germinate best at high temperatures, others at low temperatures, and further species over a wide temperature range. Many species also germinate better when a substantial diurnal range of temperature occurs. Figure 5.1 gives the main germination periods of some common annual weeds of arable land in the UK.

Perennial weeds may show some growth right through the winter even in cool climates (Figure 5.2). Time of flowering may however vary markedly between species.

Traditional methods of weed control such as ploughing or cultivation before the new crop is established, followed by hand or machine hoeing are very effective if carried out conscientiously, but are labour-intensive, especially hand methods (Table 5.4), and may be prohibitively expensive in countries with high labour costs. Additionally, continuous cropping with winter cereals, which is now a common practice in temperate latitudes, leaves only a short break for cultivation between harvesting and sowing in the cooler climate, which discourages ploughing and encourages minimum cultivation or direct drilling. Finally, weed control in mature, dense crop canopies is difficult by manual methods. All these factors

| TABLE 5.4 |
| Farmers' time spent in weeding, Western State, Nigeria (Holm, 1975) |

<table>
<thead>
<tr>
<th>Village</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akinlalu</td>
<td>74%</td>
</tr>
<tr>
<td>Edi-emi</td>
<td>61%</td>
</tr>
<tr>
<td>Ilero</td>
<td>56%</td>
</tr>
</tbody>
</table>
Figure 5.1 The main germination periods for some common annual weeds of arable land in the UK (BCPC, 1982)

- Polygonum aviculare (Knotgrass)
- Polygonum convolvulus (Black bindweed)
- Polygonum persicaria (Redshank)
- Ranunculus arvensis (Corn buttercup)
- Raphanus raphanistrum (Wild radish)
- Senecio vulgaris (Groundsel)
- Sinapis arvensis (Charlock)
- Solanum nigrum (Black nightshade)
- Sonchus asper (Prickly sowthistle)
- Spargula arvensis (Corn spurrey)
- Stellaria media (Common chickweed)
- Thlaspi arvense (Field penny-cress)
- Triglochin maritimum ssp inodorum (Scentless mayweed)
- Urtica urens (Small nettle)
- Veronica hederaefolia (Ivy-leaved speedwell)
- Veronica persica (Common field-speedwell)
- Vicia hirsuta (Hairy tare)
- Viola arvensis (Field pansy)

Aethusa cynapium (Fool’s parsley)

Althaea officinalis (Common fumitory)

Anagallis arvensis (Scarlet pimpernel)

Aphanes arvensis (Parsley-piert)

Atriplex palaestina (Common orache)

Avena fatua (Wild-oat)

Avena ludoviciana (Winter wild-oat)

Capsella bursa-pastoris (Shepherd’s-purse)

Chenopodium album (Fat-hen)

Chrysanthemum segetum (Corn marigold)

Fumaria officinalis (Common fumitory)

Galinsoga quadriradiata (Common hemp-nettle)

Galium aparine (Cleavers)

Matricaria matricarioides (Pineappleweed)

Matricaria recutita (Scented mayweed)

Medicago lupulina (Black medick)

Papaver rhoas (Common poppy)

Plantago major (Greater plantain)

Poa annua (Annual meadow-grass)
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<tr>
<th>Weed</th>
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<td>Achillea millefolium (Yarrow)</td>
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<td>Cardaria draba (Hoary cress)</td>
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<td>Chamaenerion angustifolium (Rosebay willowherb)</td>
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<td>Convolvulus arvensis (Field bindweed)</td>
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<td>Equisetum arvense * (Field horsetail)</td>
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<td>Holcus mollis (Creeping soft-grass)</td>
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<td>Mentha arvensis (Corn mint)</td>
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<td>Polygonum amphibium (Ambitious bistort)</td>
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<td>Pteridium aquilinum * (Bracken)</td>
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<td>Ranunculus repens (Creeping buttercup)</td>
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<td>Ranunculus sylvatica (Creeping yellow-cress)</td>
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<td>Sannchus arvensis (Perennial sow-thistle)</td>
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<td>Tussilago farfara (Cleat’s-foot)</td>
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<td>Urtica dioica (Common nettle)</td>
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</table>

* Non-flowering plants

Figure 5.2 The periods of growth when green foliage is present, (thin lines) and of flowering (thick lines) for some common perennial weeds (BCPC, 1982)
have encouraged widespread use of the herbicides: indeed in many cases no other method of weed control is used, and in countries such as the United Kingdom expenditure on herbicides substantially exceeds that on all other kinds of pesticide.

The main meteorological aspects to be considered in the context of operational crop protection against weeds arise in connection with herbicide drift, and the timing of sprays for both effectiveness and safety to the crop being protected.

5.2 HERBICIDE SPRAY DRIFT

Many herbicides are extremely phytotoxic to non-target plants. Especially sensitive in this respect are horticultural crops such as tomatoes and lettuce, which may be slightly damaged by doses of widely-used weedkillers at as low as 0.01 per cent of the normal application rate used to control weeds in cereals (BCPC 1983). Many other plants show a high sensitivity, including brassicas; the last include oil-seed rape which is now grown widely as a break crop in cereal rotations and so is often at risk.

In principle, the avoidance of damaging spray drift is a simple matter of not applying sprays when weather is likely to cause movement of any part of the spray towards a sensitive crop. In practice a variety of factors combine to set aside this simple precaution from time to time. Of special importance is that the crop being protected may itself become sensitive to the herbicide beyond a certain growth stage: thus if unfavourable weather occurs during the run-up to the onset of increased crop sensitivity the farmer is more likely to carry out the spraying in less than ideal conditions in order to assure timeliness of the application. Spackman and Barrie (1982) have used a set of simple criteria for optimal conditions for herbicide spraying and efficacy of action, including an upper limit of wind speed to reduce the chance of drift, in conjunction with hourly meteorological data to determine the number of optimal periods for spraying over a number of years. A plot of numbers of reported incidents of spray drift damage from part of eastern England against the estimated number of suitable spray occasions (Fig 5.3) shows an inverse relationship and demonstrates very effectively the importance.

![Figure 5.3 Spray occasions in May in Eastern England, and cases of damaging spray drift (Spackman, 1983)](image-url)
of meteorological factors in spray drift. This form of analysis was extended by Dennett and Murphy (1983) who used similar criteria for spraying and also phenological models predicting the development of winter wheat in response to temperature. By combining these results with recommendations on the growth stages between which spraying should take place with particular types of herbicide the likely number of spray occasions in individual years could be predicted and used to construct probability distributions (Figure 5.4).

![Cumulative probability distributions of the number of spraying days for a crop of winter wheat sown on 1 October (---) and 21 October (-----) for the herbicides MCPA (Bayer) (a) and 2,4-D isopropyl (b). South East England, 1972-1982 (Dennett and Murphy, 1983)](image)

5.2.1 Meteorological factors in spray drift

5.2.1.1 Spray drop drift

Most herbicide spraying is carried out using ground-based hydraulic systems with fan jets that ejection the spray liquid downwards at speeds of around 20 m s\(^{-1}\). The ejected sheets of spray liquid disrupt to form a broad spectrum of drop sizes with a mass median diameter of around 300 µm and up to 10 per cent or so of the volume contained in drops smaller than 100 µm. The fall speed of the 100 µm drops is about 0.25 m s\(^{-1}\), with an approximate proportionality to diameter squared for other sizes of up to 150 µm. Factors like wet-bulb depression (and hence drop evaporation) and atmospheric stability have some influence on the proportion of spray drifting outside the target area (Thompson and Ley, 1983; Thompson, 1983a) but the overriding influence is wind speed. At speeds where drift is likely to be a problem the turbulent air velocities are approximately proportional to wind speed. Whether the drops are likely to drift is determined by the size of the ratio of drop fall speed to vertical turbulent air velocities, and hence by ratio of fall speed to wind speed. Thus an increase of wind speed increases the upper limit of the size range of the drops that will drift significantly, as well as increasing the chance of drops within this size range of drifting further. Furthermore, higher wind speeds cause the sheets of liquid ejected from the spray jets to disrupt more quickly and therefore increase the effective release height of the drops; the amount of drift is roughly proportional to
the effective release height (Thompson and Ley, 1983), further demonstrating the importance of wind speed in controlling drift.

Some herbicide drift will occur even at very low wind speeds because of the small size of some of the emitted drops, but seriously damaging drift extending some tens of metres into a sensitive crop adjacent to the field being sprayed is unlikely to occur unless wind speeds are in excess of the maximum limit usually used when herbicides are sprayed (about 5 m s\(^{-1}\)) (Lawson, 1983): the wind would of course have to blow directly from the sprayed area to the sensitive crop to cause damage.

Herbicide spraying is sometimes carried out using controlled drop size systems, or electrostatically charged drops (BCPC, 1983). The controlled drop devices produce a nearly monodisperse drop spectrum: the mass median drop diameter is usually set at around 200 \(\mu\)m for herbicides, thus reducing considerably the risk of drift by comparison with hydraulic sprayers. The space charge produced by drops from electrostatic sprayers induces an image charge below that attracts the drops to the surface and lessens their chance of drifting.

5.2.1.2 Vapour drift

Herbicide damage to sensitive off-target plants has been reported on many occasions when the wind direction at the time of application has precluded direct drift. In these cases the damage has been caused by a wind shift after application bringing herbicides volatilizing from the sprayed crop across to the sensitive plants. The potential for vapour drift can be very large: for example, Maybank et al. (1978) found that 10-40 per cent of 2,4-D applied in an ester form to the soil surface volatilized in a few hours.

A considerable number of factors, many of them meteorologically related, contribute to the herbicide vapour hazard. As a result it is very difficult to quantify the proportion of the herbicide applied to the target area that volatilizes, and the rate at which it does so. The herbicide may reside initially partly on foliage and partly in the surface layer of the soil beneath the canopy. Subsequent volatilization from the soil will be influenced by adsorption, soil moisture and soil temperature. Loss to the atmosphere from the foliage is controlled by leaf temperature, wind speed, atmospheric turbulence, rate of absorption by the plant tissue, and the form of herbicide diluant and the physical nature of the deposited liquid (e.g. its surface area). The surface temperature of bare soil on sunny days may be at least 20°C higher than the standard air temperature (measured at a height of around 1.2m) when the soil is dry. On the other hand the volatility of herbicides applied to very dry soil can be substantially less than when the soil is moist. In the case of a crop-covered target area the leaf temperature may also substantially exceed the air temperature if the crop is water-stressed. Particularly important from the meteorological viewpoint is that the vapour pressure of many herbicides, and their rate of volatilization when in free liquid form increases by a factor of four for each 10 degree rise in temperature (Burkhard and Guth 1981).

Although it is difficult to determine the source strength of the evolving vapour, the subsequent dilution of this vapour as it moves downwind, and its likely rate of uptake by plants can be estimated (Thompson 1983b,c). It is found that this uptake falls off substantially less rapidly with increasing
distance than when the drift is in the form of drops (Figure 5.5), so that vapour drift presents the greater potential hazard. The calculations suggest that vapour damage to very sensitive crops can occur at least 200m downwind from the target area when 10 per cent or more of the applied chemical volatilizes, and drift damage has certainly been observed at these distances (BCPC 1983).

![Diagram showing predicted variations of herbicide deposits with distance downwind from edge of field 120 m long, for drop and vapour drift (from Lawson, 1983; Thompson, 1983a, b)].

- drop drift deposits from a conventional hydraulic sprayer releasing drops at 0.5 m above surface at wind speeds of A: 5 m/s and B: 2 m/s
- vapour drift deposits when C: 20% of applied chemical volatilizes and D: 10% volatilizes (wind speed 2 m/s in each case)

5.2.1.3 **Aerial spraying**

Spray droplets from aerial applications drift considerably further than applications from ground-based sprayers because of the substantially greater release height, and so in countries such as many in Europe, where monoculture over large areas does not occur, aerial herbicide spraying would only be allowed in special circumstances.

When aerial spraying does take place without risk of damage to off-target crops it is still important to avoid drift which might contaminate water supplies: in many cases this may demand still conditions, the forecasting of which may make severe demands on weather services. An example of the stringent rules governing both aerial and ground spraying of herbicides is provided by the regulations for Spain (Table 5.5) which include a precise specification of the limiting meteorological conditions.
### 5.2.1.4 Meteorological implications of herbicide drift in operational crop protection

As discussed already, spray drop drift increases sharply with increasing wind speed, and vapour drift with temperature. In order to minimize the risk of damage to off-target crops from drop drift, and to optimize the work programme, the spray operator requires accurate forecasts of wind speed and direction for the next few hours, especially a forecast of any sharp changes of wind direction, and, for planning purposes, the outlook for the following day or so. Where fairly volatile pesticides are used the operator must anticipate the possibility of vapour drift damage not just on the day of application but also for the next few days; he needs therefore accurate wind direction forecasts for at least two days ahead and a warning of any likely sharp rise in temperature.

**TABLE 5.5**

*Regulations on use of hormonal herbicides in Spain (from Order of 8 October 1973 - Ministry of Agriculture, Spain)*

<table>
<thead>
<tr>
<th>Herbicides involved (others are added as appropriate)</th>
<th>2,4-D; MCPA; 2,4,5-T; Phenoprop; Mecoprop; Dichlorprop; MCPB; 2,4-DB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formulations with high volatilities (&quot;light&quot; forms)</td>
<td>Eythyl, propyl, butyl, isopropyl, isobutyl, and amyl esters</td>
</tr>
<tr>
<td>Formulations with low volatilities (&quot;heavy&quot; forms)</td>
<td>Remaining esters, and salts</td>
</tr>
<tr>
<td>Sensitive crops</td>
<td>Cotton, crucifers, legumes, stone and pip fruit trees, sunflower, lettuce, beetroot, tomato, vine, cucumber, tobacco, thorn apple, ornamental flower and fruit bush crops</td>
</tr>
<tr>
<td>Additions for 2,4,5-T and Phenoprop</td>
<td>Populus, salix, alnus, morus, junghans, sophora, robinia, gleditschia and eucalyptus</td>
</tr>
<tr>
<td>Minimum distance of spraying from sensitive plants</td>
<td>&quot;Light&quot; herbicides  &quot;Heavy&quot; herbicides</td>
</tr>
<tr>
<td>Production of sprays</td>
<td>Ground spraying  100m  20m</td>
</tr>
<tr>
<td>Prohibited meteorological conditions</td>
<td>Aerial spraying  1000m 200m</td>
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<tr>
<td></td>
<td>Spray pressure less than 4 atmospheres; spray volume not less than 200 l/ha (ground sprayers) or 25 l/ha (aerial spraying); not more than 2% of spray volume in drops less than 100 μm</td>
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<tr>
<td></td>
<td>Temperature above 25°C at time of application</td>
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<td></td>
<td>Wind speed above 1.5 m s⁻¹</td>
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</table>
5.3 THE TIMING OF HERBICIDE SPRAYS FOR EFFICIENCY, AND SAFETY TO THE CROP BEING PROTECTED

Environmental factors play a considerable part in the effective use of herbicides, and so crop protection schemes involving weed control usually require meteorological inputs if they are to be as successful as possible. Reviews of these environmental factors have been provided by Muzik (1976) and Gerber et al. (1978). Principle considerations in the context of operational crop protection are to insure that the herbicides are used in ways which minimize the number of applications and maximize the benefits of weed suppression to the crop being protected, and its successors. At the same time the herbicides must not damage the crop in which the weeds grow.

5.4 METEOROLOGICAL FACTORS IN EFFECTIVE HERBICIDE USE

5.4.1 Soil-applied herbicides

These are usually applied before the emergence of the crop: their action on the weeds may be either through the roots or the growing shoots. Efficacy is affected by a number of factors (e.g. Eagle, 1983), particularly soil type and soil moisture; thus organic matter and clays adsorb the chemical, while availability is substantially higher for moist rather than dry soils. These herbicides usually perform best when the weeds are growing actively in moist soil and thus drawing a good supply of soil moisture (with herbicide in solution) to maintain the transpirational stream through them. In terms of operational crop protection, a major consideration is likely to be the amount of soil moisture at the time of application. For example, if the soil is very dry then an increased application rate may be needed: a forecast of significant rain in the next few days may encourage a farmer to delay spraying until the soil is moist when a reduced application rate may be as effective.

5.4.2 Foliage-applied herbicides

These may act either through contact, or by translocation throughout the weed plants. The five major factors which will affect performance are interception of the herbicide spray by the weeds, retention on the foliage, penetration into the plants, translocation and plant susceptibility.

5.4.2.1 Interception and retention of herbicides

The amount of herbicide intercepted will depend on the size of the weed plants and their leaf geometry. The nature of the crop growing with the weeds will also control interception. The primary meteorological considerations occur in connection with retention. Weed plants growing quickly in ideal conditions may have substantially different wax and hair distributions on their leaves compared to plants which have grown under conditions of water deficit and so with a different capability for spray drop retention. Heavy rainfall immediately after application will remove most of the herbicide before it has time to act properly, whereas light rain (≤ 1mm), and dew maintain the herbicide in solution and so increase the time it is available for uptake (Behrens, 1977; Caseley, 1979; Caseley and Coupland, 1980). Hot, dry and windy conditions favour rapid drying out of the herbicide solution, and reduced uptake.
CHAPTER 5

5.4.2.2 Penetration and translocation

The nature of the cuticle which covers the weed foliage varies with species, and also with antecedent and current meteorological conditions. Plants growing rapidly in warm, moist conditions have thinner wax layers on their leaves, and are penetrated more easily by herbicides; subsequent translocation is rapid in these conditions. Most evidence suggests that high humidities favour uptake of herbicide, presumably because the leaves are likely to be well-hydrated in these conditions, with maximum fissuring of the cuticle wax (Caseley, 1984).

5.4.2.3 Plant susceptibility

This depends on the species, growth stage and antecedent growing conditions, but for most herbicides it is likely to be greatest when application is in warm, humid conditions with high light intensity. Such conditions favour high biochemical activity, and rapid translocation if soil moisture is sufficient to maintain a good transpirational flow.

5.4.2.4 Meteorological considerations in operational crop protection

If other considerations allow (e.g. crop susceptibility to the herbicide), then the most favourable conditions for the application of foliar herbicides are usually warm and humid, with preferably a period of dew or very light rain soon after application to assist cuticular penetration. The warm temperatures encourage volatilization of the applied chemical, and so if a volatile formulation is used, then the prospect of increased vapour drift with possible damage to off-target crops must be borne in mind. Conditions with substantial rainfall soon after application obviously must be avoided.

5.4.3 Microbial herbicides ("mycoherbicides")

These are indigenous pathogens which have been found to attack individual weed species (Hassan, 1983; TeBeest and Templeton, 1985). Their use provides a cheaper method of controlling weeds since their development cost is only about 10 per cent that of conventional herbicides; they have particular application against weeds whose economic importance would not justify development of a more traditional type of herbicide. Several mycoherbicides are already in commercial production and many others are being developed.

Because the pathogens involved are fungi the effective use of this class of herbicide requires specific meteorological conditions: high humidity is usually needed during infection of the host plant, with a period of free water on the leaf surfaces to allow the fungal spores to germinate. The successful use of mycoherbicides requires, therefore, not only accurate weather forecasts, but also methods of modifying the forecast data to predict the environment actually experienced by the pathogens.

5.5 METEOROLOGICAL FACTORS IN THE USE OF HERBICIDES WITHOUT CAUSING CROP DAMAGE

Optimal herbicide applications are made at a time when the weeds are most susceptible, and the crop being protected is most tolerant of the herbicide, provided that competition from weeds has not already produced an
irreversible reduction of final crop yield. The length of this optimal application period will vary with crop type and herbicide, and also with meteorological conditions that determine how fast the crop grows and therefore how long it is less vulnerable to herbicide damage. Examples of the length of this optimal period are given by Tottman and Phillipson (1974) and Pessala (1983). The last author pointed out that at high latitudes, where crop and weed development are rapid because of the long summer day, the optimal application period may be as short as a few days for some herbicide/weed/crop combinations. Dennett and Murphy's analysis (Section 5.2) showed how restricted the opportunities were in some years for safe, effective use of some herbicides for which the period of crop tolerance is short.

A further consideration is that the meteorological conditions at, or soon after, application may directly affect the susceptibility of the crop to the herbicide. Thus a herbicide could be used safely, given the appropriate meteorological conditions, which might otherwise damage the crop. For example, Preston and Biscey (1982) showed that in the case of two herbicides used in sugar beet crops, one was more damaging when applied in humid, wet conditions, while the other was more damaging to the crop if the weather was warm and sunny around spraying time. There is considerable evidence (Muzik, 1976; Orson, 1983; Tottman and Farman, 1983) that some selective herbicides can cause lasting crop damage when used during frosty conditions.

Herbicide application can also cause crop losses if spraying takes place when the soil is wet, because in these conditions some types of soil can be severely compacted by the spray vehicle wheelings. The resulting loss of soil structure restricts proper plant development and causes yield losses that may extend into subsequent years (Raghavan et al., 1979). Operational meteorological advice can at times allow some alleviation of this problem, by encouraging a farmer to delay spraying until the onset of a dry period is forecast, or by bringing spraying forward, if the soil is currently dry enough to avoid severe compaction, and when heavy rain seems likely within two or three days.

5.6 METEOROLOGICAL FACTORS IN MECHANICAL OR HAND WEEDING

Weeding in dry soil conditions can present difficulties in some cases because of hard ground. In wet conditions damage to soil structure may result from soil compaction during weeding: hand weeding in these conditions may remove much soil, and weed plants disturbed by mechanical methods can quickly re-establish themselves. For reasons like these the weeding operation can be made more effective in some cases by timing it to coincide with appropriate meteorological conditions. Hoeing for example, if delayed until the onset of a warm, dry spell of weather will allow uprooted weeds to desiccate before they have time to re-root. Weeding should be brought forward with advantage if otherwise it would coincide with a prolonged wet spell. Other examples of timely weeding include hoeing to bring deeper seeds nearer the surface to germinate, but then to survive only briefly at the start of a period of dry weather.
5.7 SUMMARY

The safest and most effective use of herbicides requires operational meteorological advice in order that:

(a) spray drift damage to sensitive off-target crops, and contamination of water supplies, can be avoided;

(b) the most economical use of soil-applied herbicides occurs;

(c) foliage-applied herbicides are timed to coincide with conditions favouring rapid uptake and will not be washed off by rain;

(d) the risk of herbicide damage to the growing crop is reduced.

(e) soil compaction by the spray vehicle is minimized;

Meteorological advice is also required to ensure that mechanical or hand weeding is carried out at the most effective time.
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Nieto, J., Brondo, M.A. and Gonzalez, J.T., 1968: Critical periods of the crop growth cycle for competition from weeds. PANS, 14: 159-166.


CHAPTER 6

METEOROLOGICAL DATA REQUIREMENTS FOR CROP PROTECTION

6.1 INTRODUCTION

The aspect of crop protection that currently makes most use of meteorological data is action against harmful insects and diseases. Although more herbicides are used in many countries than insecticides and fungicides, the use of weather data in weed management (see Chapter 5) is far less developed.

This chapter will firstly use examples of pest management schemes to delineate the various meteorological variables that need to be measured or derived for crop protection. It will then consider the various ways that these data may be gathered: through networks, on farms or at standardized stations, and by remote sensing. Clearly, some of these data-gathering techniques will only be available to those countries with histories of meteorological excellence and with adequate resources. It is nevertheless to be hoped that countries with shortfalls in expertise, training, reliable long-term records, management and communication methods, and the monetary resources necessary to establish observing and data processing facilities, will find aspects of the described schemes that can be utilized at costs they can meet. It is important to describe the "ideal systems" and then see where the maximum savings can be achieved with the least degradation in usefulness of these systems.

6.2 METEOROLOGICAL DATA REQUIRED

Economically important pests and diseases range from soil-based insects and pathogens to locusts or certain spores whose spread may be strongly influenced by meteorological variables at heights well above the surface of the Earth. The development of many of these pests and diseases is determined not by average conditions over a day or so, but rather by integrating the combined effects of interacting variables, with the relevant combination sometimes changing as the pest's life cycle progresses. A proper description of the influence of meteorological factors on pest and disease development requires, in addition to the biological data, meteorological data from below the soil surface up to the lower troposphere. Relevant horizontal space scales are determined chiefly by local topography and the general variability of rainfall, and time-scales may range from fractions of a day to many weeks.

All three of historical, operational and forecast data are required. The historical data are needed, for example, to test how potential operational models of pest and disease development might have predicted past "epidemics", in cost/benefit analysis of controlled pesticide spray programmes, and in assessing the potential threat of a pest in a new cropping region. Operational data are needed in the running of operational schemes in order to give current information on likely pest and disease development rates when the need is for the data to be integrated over relatively short periods from hours or days to a few weeks. Forecast data for pest management are discussed in detail elsewhere (see Chapter 7), but must be considered in combination with operational data. For example, when observations suggest that temperature
accumulations are approaching the threshold for emergence of an insect pest, forecast temperature may determine the urgency of preparative measures or the need for hiring extra labour. If hourly forecast data are required in the simulation of the pest's development, maximum and minimum temperature forecasts combined with a diurnal temperature function (e.g. Parton and Logan, 1981) may be sufficient to make very useful management decisions.

It is difficult to agree on the minimum weather data set required for pest management. Some very useful guidance can be obtained for certain insect control schemes from temperatures alone, observed at standard weather stations (Chapter 3; Mcleod, 1981). With the addition of standard humidity observations, it is possible to quantify the climatic potential for some plant diseases (Payen et al., 1983). Thus temperature and humidity information represent the bare minimum data set required. Beyond this, Muller (1979) cautions that the decision to gather additional data should be based on study and modelling of the specific pest problem. He says we are "wasting time and money to conceive any system of meteorological data processing without this knowledge". However, he suggests that, ideally, some typical sites in an area (chosen from climatological-biological experience) should feature:

- radiation balance measurements, with separate recording of short and long wave radiation.
- nine temperature measurements: three typical leaves, soil surface, root zone, and wet and dry bulb at crop top and 1m higher;
- wind speed and direction at same two heights as for wet and dry bulbs;
- three wetness recorders at same sites as leaf temperature measurements.

In practice it is usually not feasible to gather the comprehensive data set that Muller proposes, and workers will have to use some information gathered at standard weather stations combined with a few crop measurements or perhaps with models which infer crop climate from standard data.

6.2.1 Temperature

Temperature is the meteorological variable most used in pest management. It plays an important role in the development of pests living in the soil, air or plant parts, and also in the phenological development of the host crop.

6.2.1.1 Insects

For insect pest management the most common technique involves the use of "heat unit" or "degree-day" accumulations (Pruess, 1983; Collier and Finch, 1985). In its simplest form the degree-day (DD) computation for a single day takes the form:

\[
DD = [(T_{max} + T_{min})/2] - T_{base}
\]  

(1)

where T_{max} and T_{min} are the observed maximum and minimum temperatures for the day. The parameter T_{base} is a threshold temperature below which no further
development of the pest is expected. This parameter is usually determined in controlled studies of the insect. Values of DD are accumulated day after day and the arrival of the pest at various stages of its life cycle is signalled by specific DD totals. Use of an appropriate DD total can thus allow the timing of a control measure to coincide with a vulnerable stage (e.g. the use of a foliar insecticide when leaf-eating larvae emerge).

More elaborate insect management schemes have been developed where the degree-day accumulation signalling a certain life stage is modulated by previous weather. For example, the cumulative emergence (E) of European corn borer (Ostrinia nubilalis, Hbn.) in eastern Canada has been related to DD by an equation of the form (MoLeod, 1981):

\[ E = a + b(DD) \]  \hspace{1cm} (2)

where the slope (b) and intercept (a) of this linear equation are determined by mean temperatures for several past months (related to overwintering survival) and the previous year's borer population. Non-linear curve-fitting has been used in other temperature-dependent models of European corn borer (Anderson et al., 1982a, 1982b).

Depending on the habitat of the insect, the best model results may be obtained with soil, air, leaf litter, or plant temperatures. Except for air temperatures, these usually should be measured "on site" since the conditions in or under the grass at a meteorological station are very different from those at the insect's location. For aerial stages of insect life, standard screen temperature data have sometimes been successful predictors of development (MoLeod, 1981), perhaps because warmer-than-screen daytime crop temperatures are compensated for by cooler crop values at night. Probably due to the same compensation and the great difficulty of measurement, plant temperatures are not required in any known operational pest management scheme, except as a computed intermediate step in estimating surface wetness duration (see section 6.3.5).

6.2.1.2 Diseases

Temperature also controls the growth rate of many plant disease organisms, but nearly always in combination with moisture (see section 6.2.2). The use of temperature may vary from specifying a threshold such as 10°C for potato blight (Bourke, 1955), a single range such as a "mildew hour" where temperatures must simply be between 15-25°C (Lomas et al., 1971), or many more finely divided categories (Madden et al., 1978). If the scheme was developed empirically from standard weather data (e.g. Bourke, 1955) then screen temperature data from a standard station may be used. However, when such empirical schemes are not based on fundamental theory linking crop climate with standard data, the schemes may not be transportable from one site or climatic zone to another. Other schemes which are derived from controlled environment studies require temperature data from screens or shielded thermometers in the crop (MacKenzie, 1981; Madden et al., 1978).

6.2.1.3 Summary

1. Temperature is used in all weather-based insects and plant disease management schemes.
2. Standard weather station air temperature data are sufficient for schemes involving aerial life stages of insects and some empirically-derived disease management systems.

3. For disease management systems derived from fundamental controlled environment studies or for schemes involving soil- or litter-borne insects, standard station data are usually inadequate. Measured or derived temperatures in the pest organism's habitat are required.

4. Measurement of plant temperature is not needed in any known operational pest management system.

6.2.2 Moisture

Moisture is an essential element of most plant disease prediction schemes and is also essential to outbreaks of some insect pests.

The moisture data required will vary with the application, but include relative humidity, rainfall, and surface wetness duration. Soil moisture may also be important, for example in the activity of herbicides (Chapter 5) and soil-dwelling insects. There are considerable difficulties in spatial sampling when using gravimetric soil moisture determinations, and of cost with more modern methods such as neutron probes. The most attractive approach for pest management is probably the modelling of soil moisture, using rainfall and other meteorological data along with knowledge of the properties of the soil and crop: even this approach, however, may encounter difficulties when conditions at the soil-atmosphere interface are of particular concern.

6.2.2.1 Relative humidity

Dry- and wet-bulb psychrometers and also hygrothermographs are widely used at standard weather stations, auxiliary stations or crop sites to monitor relative humidity (RH). Certain disease organisms respond directly to RH such as downy mildews on grapes (Lomas et al., 1971) and on onions (Hildebrand and Sutton, 1982), where germination begins when RH >85-90 per cent. There are some xerophytic powdery mildews found in arid countries that are limited by high atmospheric humidities (Palti, 1961), and RH may also affect certain insects (Coscoilla, 1980; Omar, 1980).

It would be best if the RH data were obtained in the crop near the site of pest development, but it may be satisfactory to use standard weather records in some cases. If temperature is measured (or well estimated) in the crop, it is possible to synthesize a good approximation to the crop RH from the vapour pressure (e) measured at a nearby weather station using the definition of RH = e/e_s, where e_s is the saturated vapour pressure at the temperature of the crop. This is because e is one of the most conservative quantities in an air mass and this fact has also been used in dew modelling (Pedro Jr. and Gillespie, 1982).

RH is often used in disease forecasting schemes where the organism really responds to the presence of liquid water, rather than high humidity alone (MacKenzie, 1981, Figure 6.1; Madden et al., 1978; Bourke, 1955). In other words, the duration of RH greater than some threshold (usually 85-90 per cent) is taken as an approximation of the duration of liquid wetness on plant
parts. This practice has probably resulted from the difficulty of measuring surface wetness duration (SWD), and the subsequent lack of such data in operational systems. However, several studies have shown that the approximation of SWD by RH > 90 per cent is sufficiently poor (Lomas and Shashoua, 1970; Crowe et al., 1978; Thompson, 1981) to cause serious errors in estimating disease progress.

![Graph showing the relationship between likelihood of infection, hours of RH > 90%, and daily severity values.]

Figure 6.1 A suggested relationship of the duration of high relative humidity periods and the average temperature during that period to the likelihood of infection and the corresponding severity value of potato late blight (Phytophthora infestans) (after Mackenzie, 1981)

6.2.2.2 Rainfall

For plant disease development the timing, duration, or rate of rainfall are often more important than the amount of precipitation. The onset of rain clearly marks the beginning of a period of surface wetness, and the duration of the rain sets the lower limit for the total duration of wetness. Rate of rainfall may influence spore survival (Hildebrand and Sutton, 1982) or spore dissemination (Hunter and Kunimoto, 1974). Total rain over some period of time (e.g. the past 7 days, Madden et al., 1978) sometimes is used in empirically derived systems where it may be functioning as a rough approximation of the accumulated duration of wetness.

Precipitation, or its absence, can regulate insect pest damage by direct impingement when they are exposed, through soil moisture when they are in the ground, or by affecting natural enemies (Bierne, 1970). Effects can be both helpful and harmful to control schemes. Flooding may kill by drowning or by forcing soil pests to the surface where predators wait, but may also disperse soil pesticides. Drought may crust the soil surface and prevent insect emergence, or may force pests to remain at depths where control is impossible. The influence of precipitation on soil moisture and subsequent locust swarms is well documented (see section 4.2). High rates of rainfall are often lethal to small exposed insects, or to small stages of insects such as newly-hatched larvae.
A major difficulty in operational pest management systems is coping with the spatial variability of rainfall. Especially for those countries and seasons where the rainfall is mainly from mesoscale convective activity, an adequate raingauge network and a centralized feedback system in order to give proper pest management advice over large areas seems almost unattainable, although radar detection offers some hope (see section 6.3.2.2).

6.2.2.3 Surface wetness duration

Although not generally considered as a true meteorological variable, surface wetness duration (SWD) caused by rain, dew or fog is of paramount importance to plant diseases in a wide variety of crops, such as apples (Post et al., 1963), wheat (Prabhu and Prakash, 1973), rubber (Paes de Camagro et al., 1978), carrots (Gillespie and Sutton, 1979), onions (Hildebrand and Sutton, 1982), tomatoes (Madden et al., 1978), and more.

This variable is difficult to measure well and shows considerable spatial variability (Figure 6.2) over very short distances due to

Figure 6.2 Time of drying of onion foliage measured by electrodes clipped on the leaves relative to that measured by a dewit recorder on various days in the growing season. The leaves usually dried before the hemp-string sensor of the recorder early in the season but after the hemp-string sensor late in the season (after Sutton et al., 1984)

... differences in radiation, wind and exposure to rain. Various instruments have been devised to monitor SWD (Post et al., 1963) with a tendency in recent years to move away from mechanical types toward battery-powered electronic systems (Gillespie and Kidd, 1978; Pinguet, 1983; Sparks and Wass, 1983). It appears that at least two sensors positioned in the crop (one in the upper quarter canopy for dew, one in the lower canopy for rain) are required to monitor the "worst case", which should be used for disease management. Data logging systems capable of simultaneously monitoring several wetness sensors are commercially available. There is currently no agreement on the best type or location of sensors, but the total exposure to wind and radiation experienced by an SWD instrument over turf at a standard weather station will certainly not allow it to mimic crop conditions.

Standard radiation, wind, humidity and temperature data may be used to estimate crop SWD from micrometeorological models (see section 6.3.5).
6.2.2.4 **Summary**

1. Relative humidity controls the survival of some plant disease organisms and RH data are therefore required in associated control schemes.

2. RH data taken in, or extrapolated to, the crop are usually preferred but standard weather station data appear to suffice in a few cases (e.g. when a scheme was derived empirically from the station data).

3. Although duration of RH >85-90 per cent has been used as a substitute for surface wetness duration, the agreement has proved to be poor.

4. Timing and duration are the two most important rainfall parameters in disease management schemes. Amount of rain is used in some empirical schemes as an indicator of length or frequency of moist periods.

5. Precipitation amounts are required for management of insects dependent on soil moisture. High rainfall rates have the potential to reduce populations of small insects, but such information is not currently used in operational pest management schemes.

6. Spatial variability of rainfall creates major problems in establishing centralized pest management systems.

7. Surface wetness duration measurements made at a standard weather station will generally not suffice for management of plant diseases.

6.2.3 **Wind**

Both wind speed and direction, and both surface and lower tropospheric winds have applications in pest management schemes. Near-surface winds will control short distance dispersal of insects and disease spores (Ayler and Lukens, 1974; Hunter and Kunimoto, 1974) and will profoundly influence the dispersion of pesticide sprays (Thompson, 1983; Chapter 5). Wind speed indirectly affects disease progress through its influence on latent and sensible heat fluxes so surface wind data are required to estimate crop temperatures and wetness durations from weather station data (Thompson, 1981). For longer range transport of insects or spores, wind profiles of speed and direction may be required up to the 3km level. Sources of invading pests may be identified using back-trajectory techniques or forward trajectories may be used to forecast the movement of insect swarms or spores (Wiktelius, 1977). In summary:

1. Near-surface wind speeds are needed in operational pest management to deduce crop microclimates from weather station data.

2. Wind speed and direction data up to 3km may be required for backcasting and forecasting of long range insect and spore transport.

6.2.4 **Radiation**

Radiation may affect pest management systems in both direct and indirect ways. Many disease organisms cannot tolerate very much exposure to solar radiation. They may be killed by dessication or affected by the ultraviolet, red and near-infrared components of sunlight (Leach, 1967). As
an example, intermittent periods of surface wetness may be summed in apple scab management provided that the intervening dry periods do not experience bright sunshine that would destroy the vulnerable, partly-germinated spores. Night length may influence such aspects of a disease cycle as sporulation. Light levels also affect the activity of certain insects (Coscolla, 1980) and may play a role in the timing of control measures.

Indirect effects of radiation, as in the case of wind, are related to their influence on crop temperatures and latent heat fluxes. Extrapolations from weather station to crop require both solar and long wave radiation data as inputs to the linking equations (Norman, 1982). In the absence of direct measurements, these fluxes may be estimated from cloud cover data (Pedro Jr. and Gillespie, 1982), but it must be emphasized that hourly observations may be required day and night. If incoming radiation measurements are used, the practical difficulty of keeping the instruments free from dew at night and in the early morning must be recognized.

In the context of crop protection:

1. Solar radiation information is required to assess the survival of certain spores during periods of intermittent wetness.

2. Night length controls phases of the life cycle of certain disease spores and insects and may therefore modulate the need for control measures.

3. Control of activity in certain insects by light levels may sometimes be used to advantage in management schemes.

4. Solar and long wave radiation measurements, or estimates from cloud data are needed for extrapolations from weather station to crop.

6.3 NETWORKS AND DATA PROCESSING

6.3.1 Introduction

Because the provision of weather information for pest management requires consideration of micro-, meso- and macro-meteorological scales, the spatial and temporal demands on the data are very high. The significant microclimatic changes that occur from beneath the soil surface near the crop top are important. Mesoclimatic differences induced by topography or nearness to water bodies must be recognized, and synoptic scale data are needed for forecasting and for consideration of long range transport. One philosophy which reduces somewhat the immensity of this problem is to provide guidance for the "worst case" on a farm: that is, the warmest or wettest location, where a pest problem is likely to develop first. This idea builds an element of safety into the management system.

Ideally, the adequate provision of meteorological services to pest management probably requires a combination of the following data gathering and processing networks (Figure 6.3):

1. Measurements made by growers or pest consultants in crops on individual farms with no exchange of this data. There is a danger here that misreading or misinterpretation of the data may occur, since no meteorological expertise is used.

3. Measurement made at existing standard weather stations, ideally supplemented with automatic stations to cover the meso-scale, and used either directly or as inputs to models that simulate crop microclimates.

![Diagram](image)

Figure 6.3 Personnel and principal information flows associated with integrated pest management in Michigan (after Croft et al., 1978)

To truly monitor the meteorological environment would require a prohibitively dense network of observing systems. So an important aspect in assessing the meteorological data requirements for pest management is to judge how far one can use quantitative methods in order to predict vertical profiles of relevant variables in the soil and air layer from measurements at, say, a single height, or to estimate over what horizontal scale a single observation might apply. There must be some compromise between the ideal network and practical reality.
6.3.2 Space/time resolution requirements

6.3.2.1 Introduction

The resolution required will depend on the pest or disease of interest, and the complexity of the geographical region. The European experience suggests that in the absence of significant topographical variations or synoptic contrasts and within similar crops, the quantities air temperature, vapour pressure, wind, and daily solar radiation will vary only slowly spatially. Soil temperature will be more affected by soil moisture status and hence antecedent rainfall and, even in the absence of spatial variations of soil type, will be less spatially conservative in those regions where rainfall is often inhomogeneous. Spatial variations of rainfall, particularly in convective conditions or in regions with substantial topographical variations, are a source of considerable difficulty in crop protection schemes that are partly based on meteorological data from a limited number of synoptic stations (see section 6.3.2.2).

For much data a station spacing of 50 km or so will suffice, provided rainfall (thus leaf wetness), and in some cases the coincidence of intermittent dry periods and bright sunshine, can be measured at much higher resolution. A conventional network that is adequate for synoptic meteorology will provide a satisfactory data base for some purposes (Payen et al., 1983), at least away from hilly areas and shorelines. The WMO "Guide to Meteorological Instruments and Methods of Observation" may be consulted for further details on recommended network density (WMO, 1983).

Lower tropospheric flows of interest in insect migration and long-range spread of spores would usually be monitored satisfactorily twice or four times daily by conventional radiosonde windfinding networks with 200 to 400 km spacing, especially if supplemented by surface wind data from the synoptic network. Exceptions would again occur in the vicinity of steep topography or major shorelines.

6.3.2.2 Rainfall variability

Rainfall is often so variable in space and time that only an impractically dense network of stations would suffice to give satisfactory advice on probable pest or disease development at all locations. The inadequacy of standard networks has been admirably demonstrated by Schroeder (1983) who showed a dramatic degradation in the accuracy of an eyespot development model for winter wheat when on-site data were replaced by standard data from a site 10 km away in complex terrain, or from 30 km away in a coastal area.

Two possible solutions to this difficulty are on-site grower observations (see section 6.3.3) and, for some countries, quantitative radar data. Present limited experience suggests that radars spaced about 150 km apart can provide a useful supplement to conventional networks. They appear to be more accurate in detecting whether or not rain is falling rather than measuring how much. However, for many aspects of pest management a yes/no statement will often be sufficient by itself. So it appears that radar is a useful tool that can give operational (say hourly) rainfall information on approximately a 5 x 5 km basis.
On a larger scale there may be useful information in certain satellite imagery. Rainfall in large, poorly monitored arid regions may be detected by the consequent surface albedo change and this has been used operationally by FAO in predicting sites of locust multiplication. Communication via satellites may also allow more facile exchange of data in "real time" in the future.

6.3.3 In-crop sensing

Data taken on-site may be used in pest management systems in two basic ways. Either the grower/manager is provided with "factsheets" which guide the decision-making for a local area and the data are not exchanged, or the data are transmitted to a central location for analysis and recommendations from professional pest specialists. In both cases there are some distinct advantages in in-crop monitoring:

1. The environment actually controlling the pest/disease development is being measured (if the sensors are exposed correctly at the proper heights).

2. Such information could well lead to accurate local area disease forecasts, giving good advice to a number of nearby farmers.

3. Farmers would have confidence that the data being used to reach decisions are truly representative of their land.

Disadvantages of totally localized systems are that individual users may misinterpret the information obtained or may not recognize that an instrument is malfunctioning. Networking to a centralized location involves more cost and complication but insures expert advisory information and insures access to climatological data when applicable.

For such systems to be attractive and useful to the individual farmers there must be available cheap, robust and exceptionally reliable instruments that are easy to install and with correct exposure. Fulfilling this need is an important challenge to instrument specialists. In the past, mechanical hygrothermographs and leaf wetness recorders (Post et al., 1963) have given frequent problems with inking, clock drives and calibration drifts. Modern electronic devices (Gillespie and Kidd, 1978; Fisher and Lillevik, 1977; Sparks and Wass, 1983) are proving more reliable but have not yet been built in sufficient volume to reduce the cost adequately. Such instruments should incorporate microprocessors which do some moderate manipulation of the data to display, for example, average temperature and duration of wet periods, degree-day above programmable base temperatures, hours of RH >95%, etc. The advisability of going even further and incorporating disease models which use the data to produce an index of infection severity is debatable, since reprogramming as model improvements occur is difficult.

It should be noted here that specialized forecast information will still often be required to blend with in-crop sensing for optimum decision-making (Chapter 7).
6.3.4 Automatic weather stations

In the "developed" world the decreasing cost of electronic devices and the relatively high cost of labour makes the use of automatic weather stations (AWS) instead of 24-hour, manually operated ones more attractive. The AWS is well-suited to fill gaps in the observing network for pest and disease prediction because it can readily monitor all the meteorological variables of interest. Particularly in areas with considerable topographical constraints, a special network with close spacing can be set up for purely agricultural purposes, with data being fed to a central location. The extra costs and problems associated with collecting and organizing the AWS data must not be forgotten, but cost/benefit analysis may justify such a network (particularly for spatial coverage of rainfall and surface wetness) even in uncomplicated terrain.

The difficulties of building and running an AWS network should not be minimized, and in the development stage it is probably necessary for data control to run some automatic stations simultaneously at the sites of more conventional meteorological stations. Once the instruments and data have proved reliable, the rewards for initial frustrations and perserverence will be considerable.

Less developed countries at present use conventional meteorological stations, but these do not always produce reliable data. In such cases, or in remote areas, reliable AWS stations could provide better data than present systems if a few highly-trained technical personnel were available for maintenance. Considering the difficulties of acquiring such personnel, and of foreign currency, it might be recommended that a programme should begin with a single station where experience could be gained and training occur over a couple of years before further expansion. At best, a practical goal would probably be a sparse network of fully-equipped stations measuring the more spatially conservative variables, but also many more simple stations.

6.3.5 Extrapolating from weather station to crop

Where in-crop data cannot be measured, or have not been as in retrospective studies of past pest outbreaks, it is necessary to infer the climate in the crop from weather station data using a linking model. Such models involve some or all of crop temperature, wind speed, humidity, radiation and surface wetness duration. Three broad categories, in order of complexity are:

1. Empirical models using regression techniques for direct linkage to a measured variable, such as crop temperature from weather station temperature (Rahn and Brown, 1971). These are generally site-specific and may not apply at new locations. The relationships will also change with stage of crop growth.

2. A mixture of fundamental theory with some empiricism to link a derived variable such as dew duration to several variables measured at the station (Pedro Jr. and Gillespie, 1982; Gillespie and Barr, 1984, Figure 6.4). Such models are often still simple enough to run on a programmable calculator.
3. Fully developed crop boundary-layer models that have the potential to mimic all variables throughout the crop canopy, and may include the soil (Thompson, 1981; Norman, 1982). Such treatments become increasingly complex and require full computing capability, especially when microclimate estimates are sought near or below the soil surface.

The complexity and uncertainty of certain portions of the theory involved in fully developed models leaves them as research tools at present. Operational pest management schemes can be based on empirical or semi-empirical linkages derived from relatively short periods of simultaneous crop and weather station observations (Gillespie and Barr, 1984). However continuous in-crop monitoring is still a more reliable technique, where possible.

6.3.6 Accuracies required in observations

Comments here must be general, in view of the varying responses of different pests and diseases to meteorological factors. In general, the WMO "Guide to Meteorological Instruments and Methods of Observation" should be consulted, and these standards achieved wherever possible. Practical constraints may demand some relaxation of these standards under some conditions.
Thermometer accuracy requirements of ±0.2°C are "economic and suitable" according to the WMO Guide (Table 4.1, WMO, 1983). When reading and shielding errors are considered, the air temperature data from such thermometers probably have an error band of 0.5–1°C, but this would normally be adequate for pest management. However, wet bulb depression should be measured with an accuracy of better than 0.5°C in order to keep RH errors <10 per cent for temperatures above freezing (see section 5.2.5.4, WMO, 1983). Since some disease organisms that react to high humidity may change their responses very rapidly with small changes in RH, the WMO accuracy requirement of ±1 per cent (Table 2, WMO, 1983) should be sought for humidities >85 per cent, although this is a difficult goal.

On-site rainfall amounts are required in some disease and insect management schemes, and in soil moisture budgeting. WMO standards for Agricultural Meteorology are 0.2mm up to 10mm and ±2 per cent for greater amounts (Table 2, WMO, 1983). Errors of up to 10 per cent in the present context would normally be unimportant. Unfortunately, the accuracy of quantitative radar data is often very low but occurrence or non-occurrence is satisfactorily measured with this technique. Surface wetness duration measurements to 10 per cent (e.g. 1 hour in 10) would be adequate for useful prediction.

Desirable goals for bright sunshine and solar radiation measurements are ±0.1h in any hour (i.e. 10 per cent) and ±1MJ m⁻²d⁻¹ (Table 2, WMO, 1983). Standards of accuracy within 10 per cent should certainly be satisfactory for operational pest management. Conventional wind-measuring systems provide sufficient accuracy for some of the wind data requirements in operational pest management such as trajectory analysis. However, applications such as spray drift and dew duration estimates may require wind information at velocities that are below the starting speeds of the anemometers used in synoptic networks.

6.3.7 Summary

1. Comprehensive meteorological monitoring for pest management requires a combination of in-crop and weather station measurements.

2. The space/time resolution of a good synoptic network (~ 50 km) is often sufficient for monitoring wind, humidity and temperature for pest management. Exceptions are near complex topography or coastlines. However, the natural variability of rainfall, and sometimes sunshine during intermittent dry periods, requires better resolution in all regions.

3. Radar and automatic weather stations can provide some of the required increase in resolution.

4. In-crop sensing provides the ultimate resolution, but much work is needed on suitable instruments and networking.

5. Estimation of crop climates from standard weather data is at present possible to a limited extent.
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CHAPTER 7

APPLICATION OF WEATHER FORECASTS TO OPERATIONAL CROP PROTECTION

7.1 INTRODUCTION

The preceding chapters have demonstrated the close relationships between climate and weather on the one hand, and the geographical distributions and seasonal development of plant diseases and pests on the other.

Responses to a questionnaire (described in Chapter 8) show that many countries are now using agrometeorological information in their disease and pest control strategies and tactics. However, the systems adopted are more often based on observed data (current and past weather data) rather than weather forecasts. It is certain that crop protection measures can be enhanced in value when the agrometeorological data they use include forecast information. One benefit, for example, is that preventative rather than curative treatments may then be used (Chapter 2), with better control of disease. It is recognized that it is often difficult to make confident forecasts of the relevant weather elements, even for a short time ahead. In spite of this, weather forecasts already have applications in monitoring insect migrations, pest and disease development and management of chemical treatments: continuing improvements in forecast accuracy will progressively enhance and broaden these applications.

The three main sections of this chapter describe briefly the type of weather forecast and the products likely to be of use to plant pathologists, entomologists and weed control specialists, provide examples of some biologically and agriculturally related information required for the preparation of forecasts, and give examples of actual and potential applications.

7.2 WEATHER FORECASTS

The weather-related elements that most commonly influence disease and pest patterns and which are used in information and warning systems are temperature (usually maximum and minimum), relative humidity, rainfall (amount and duration) surface wetness duration (often related empirically to rain or dew), soil moisture, wind speed and direction, and sunshine (or cloudiness). All these elements may be forecast routinely, but accuracies vary with the element concerned, the geographical location and the synoptic type; however, as McQuigg (1965) points out, forecasts do not have to be perfect to have economic value. The most value is gained from them when meteorologists and crop protection specialists are mutually aware of the extent of the skills and knowledge of each other's field.

Weather forecasts of value in crop protection cover a wide range of time scales. In all cases, however, they may require significant modification in order to account for local effects (topography for example) when applied to particular places within a geographical region.
7.2.1 Very short-range forecasts

These are for periods up to only a few hours ahead. They depend on detailed meteorological observations, analyses of current weather, and techniques for projecting this information a short time into the future.

One of the most important aspects of this type of forecast is the promptness of data handling, from observation to the dissemination of the result to the end user. Developments in meteorological satellites, quantitative (precipitation) radars, telecommunication systems and computers (especially minicomputers and peripheral facilities such as graphical displays) have allowed the development and implementation of highly automated, very short-range forecasting systems in a number of countries. Examples of such systems which are operational or should soon become so include FRONTIERS (UK: Carpenter and Browning, 1984), PROFS (USA: McDonald, 1984), PROMIS-90 (Sweden: Bodin et al., 1984) and ARAMIS (France: Gilet, 1984). These schemes can also incorporate modern statistical forecasting techniques such as GEM (Generalized Exponential Markov; Perrone and Miller, 1985).

There are many difficulties in developing and implementing the highly automated systems such as those mentioned; therefore, it is unlikely that the present largely subjective and not computer-based very short-range forecasting in many countries in WMO regions RAI, RAI, RAIII and RAV especially, will be replaced rapidly by these other methods.

7.2.2 Short and medium-range forecasts

The time-scale of these predictions ranges from a few hours up to about one week ahead. They are produced chiefly by numerical weather prediction models, with interpretation provided by either the human forecaster or by statistical methods. The model outputs are provided at grid points on a scale determined largely by the computing power available and the maximum length of the forecast period. The United Kingdom system for example comprises a global forecast model (grid length about 150 km) for up to six days ahead, a "fine mesh" model (grid length 75 km) for a more limited area up to 36 hours ahead, and, under development, a mesoscale model (grid length 15 km) for a much smaller area with outputs produced up to about 18 hours ahead. In general, the detail in the model forecast declines as the grid length increases, and the forecast accuracy of course decreases with the increase in forecast time. The medium range forecasts in particular should be interpreted as providing only a general indication of the likely evolution of the sequence of weather.

Unless the models include realistic, physically-based representations of the atmospheric processes, particularly within the boundary layer, it is not usually possible to use the model outputs without some interpretation: this is particularly in the case of the coarser mesh models over irregular terrain or near coastal regions where the grid length is usually too large to describe the observed horizontal inhomogeneity (even mesoscale models may be inadequate in this respect).
APPLICATION OF WEATHER FORECASTS

Interpretation of output is increasingly based on the use of statistical methods that derive the required weather elements from the forecast fields; however, it is often found that further interpretation of these statistical forecasts by a human forecaster will produce an additional enhancement of accuracy. One advantage of the statistical methods is that, once the system to implement them is set up, further forecast elements can be produced with little additional effort. They are valuable when the required forecast element is one rarely predicted by a conventional forecaster and usually therefore subject to larger error than quantities like air temperature.

The two main statistical methods used with the short- and medium-range forecast outputs are perfect prognosis (PP) when it is assumed that the model prediction is perfect, and model output statistics (MOS) when the statistical model is derived by comparing observed values of the predictand with the model predictions, over the expected forecast range. MOS is most often used because of several advantages including automatic removal of numerical model bias, the ability to produce site-specific estimates of forecast elements and the provision of forecast estimates of quantities that may not be direct model outputs, e.g. sunshine.

Categorical forecasts do not include the degree of uncertainty associated with the forecast. The percentage risk of weather events may be indicated by a probability interpreted as the forecaster's confidence factor for the occurrence of these events. Such forecasts can have important applications in crop protection.

It is unfortunate that numerical weather prediction is less satisfactory for the tropical regions than at higher latitudes. This stems from the fact that many of the existing numerical techniques are not well suited to the tropics where coupling between wind and mass fields is weak. There are also problems to be overcome in satisfactorily initializing the models at low latitudes and in dealing with the convection processes which are so important in these regions.

The forecast meteorological elements of particular concern in insect pest and disease development, spray application and airborne movement of insect pests, include temperature, humidity (dewpoint), rainfall, wind velocity, sunshine and cloud amount, in both deterministic and probabilistic terms, over a variety of forecast-time-scales. These requirements are summarized briefly in Table 7.1. This forecast matrix can be filled economically, and updated several times daily, using largely automatic statistical interpretations of forecast model outputs which also allow the matrix values to be tuned to particular sites or geographical areas.
CHAPTER 7

TABLE 7.1

Example of a matrix of forecast meteorological data for use in operational crop protection

<table>
<thead>
<tr>
<th>Element</th>
<th>Time ahead (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 3 6 9 12 18 24 36 48 72 96</td>
</tr>
<tr>
<td></td>
<td>3 6 9 12 18 24 36 48 72 96 120</td>
</tr>
<tr>
<td>Max temp.</td>
<td>* * * * * * * * * * * *</td>
</tr>
<tr>
<td>Min temp.</td>
<td>* * * * * * * * * * * *</td>
</tr>
<tr>
<td>Wind speed</td>
<td>* * * * * * * * * * * *</td>
</tr>
<tr>
<td>Wind dir.</td>
<td>* * * * * * * * * * * *</td>
</tr>
<tr>
<td>Rainfall</td>
<td>* * * * * * * * * * * *</td>
</tr>
<tr>
<td>Probability 0 mm</td>
<td>* * * * * * * * * * * *</td>
</tr>
<tr>
<td>&gt;x1 mm</td>
<td>* * * * * * * * * * * *</td>
</tr>
<tr>
<td>&gt;x2 mm</td>
<td>* * * * * * * * * * * *</td>
</tr>
<tr>
<td>etc.</td>
<td>* * * * * * * * * * * *</td>
</tr>
</tbody>
</table>

7.2.3 Monthly and seasonal outlooks

These are produced routinely in a number of countries by several different methods but they usually show a very low level of skill at present compared to the forecasts just described. However, even the use of climatological averages alone may be helpful in estimating the likely development, extension or modification of a pest or disease in a particular year, so allowing a reasoned programme of inspection and control to be prepared in advance.

7.2.4 Observations of cumulative conditions

Observations of cumulative conditions (such as temperature or rainfall) are not forecasts in the strict sense, but they do provide useful bases for decisions and can be coupled effectively with other predictions. As an example, current data in the form of degree-day accumulations are used for the provision of advice concerning the probability of European corn borer (O. nubilalis) activity (see Chapter 3), and forecast data for a few days ahead may be used with them to improve advice as to when control measures should be taken.

7.3 REQUIREMENTS FOR APPLICATION OF WEATHER FORECASTS TO CROP PROTECTION

Application of weather forecasts to operational crop protection involves the use of qualitative descriptions and quantitative estimates of the critical levels of various weather elements relative to disease and pest appearance and development. Some of the earlier chapters have included examples of criteria and thresholds found in pest and disease patterns. A few examples are now provided to illustrate further the primary data and
information requirements that help weather forecasters to issue forecasts for crop protection.

7.3.1 Wind speed in crop spraying

Optimal speeds for spraying vary somewhat with the method of application and type of chemical used. Spraying in strong winds leads to uneven spray deposits on the field, and a much higher spray drift with the consequent risk of contaminating water supplies or damaging sensitive off-target crops. In very light winds the wind direction is often unpredictable, and although drift is small in these conditions it may be important when spraying herbicides near sensitive crops. Low levels of atmospheric turbulence in light winds also contribute to reduced deposition of spray drops on downward facing surfaces of plants. The best conditions for most chemical applications are found within the speed range from 1 to 5 m s\(^{-1}\).

7.3.2 Criteria used to forecast leaf wetness duration (SWD)

Various sets of rules have been developed for the prediction of the duration of leaf wetness of different crops after wetting by rain or dew. It is impossible to combine them into a single set of guidelines because of geographically-related differences of climate, different plant canopy structures and different favoured sites within the canopies for disease development. The rules given below were deduced from observations on carrots in one area of Canada by Gillespie and Sutton (1979), and would probably require adjustment for use at other sites.

(a) In the absence of rain, SWD was predicted as night length plus 4 h when:
   (i) expected wind speeds at 10 m above ground level were < 4 m/s and expected cloud cover was 0 to 50 per cent.
   (ii) expected winds < 2.5 m/s and cloud cover > 50 per cent.

(b) In the absence of rain, SWD was predicted to be too short for infection (by alternaria leaf blight) when
   (i) wind speeds were > 4 m/s regardless of cloud cover.
   (ii) wind speeds were > 2.5 m/s and cloud cover was >50 per cent.

(c) When rain occurred during the day, but ceased or was expected to cease sufficiently early for leaves to dry during daylight hours, SWD was forecast as expected rain duration plus 7 h.

(d) When rain was expected to end at night, or late in the day such that leaves would not dry before sunset, SWD was forecast as time between rain commencement and sunrise plus 7 h.

7.3.3 Weather requirements for some crop protection operations for rice farming in the humid tropics.

Table 1 lists the weather requirements for some crop protection activities in rice farming.
### TABLE 1

Weather conditions for crop protection operations in humid tropics rice farming (after Lomotan and Baradas, 1983)

<table>
<thead>
<tr>
<th>Operation</th>
<th>Sky condition</th>
<th>Soil moisture condition</th>
<th>Leaf Wtteness Duration</th>
<th>Air temp. (°C)</th>
<th>Wind speed m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPRAYING PESTICIDES</td>
<td>Clear day desired; cloudy and/or night acceptable. Visibility adequate for low-level flight of aircraft</td>
<td>S1—Moist or dry desired in upland farms</td>
<td>Leaves dry at spraying time no rain until at least 4 hours after spraying</td>
<td>&lt; 33 desired</td>
<td>&gt; 15 desired</td>
</tr>
<tr>
<td>S1: ground application</td>
<td></td>
<td></td>
<td></td>
<td>S1. 0–5</td>
<td>S2. 1–4</td>
</tr>
<tr>
<td>S2: aircraft application</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DUSTING PESTICIDES</td>
<td>Same as for above</td>
<td>Same as for above</td>
<td>Leaves wet at dusting time but no rain until at least 4 hours after dusting</td>
<td>&lt; 33 desired</td>
<td>&gt; 15 desired</td>
</tr>
<tr>
<td>BROADCASTING CHEMICALS</td>
<td>Clear or cloudy day desirable</td>
<td>Moist desirable</td>
<td>Leaves dry at broadcasting time</td>
<td>≤ 40 desired</td>
<td>≥ 15 desired</td>
</tr>
<tr>
<td>(pre-emergence herbicide or systemic pesticide granules/tertilizer)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HANDWEEDING/CULTIVATING</td>
<td>Clear to partly cloudy day</td>
<td>Moist or dry</td>
<td>Not critical</td>
<td>≤ 40 desired</td>
<td>≥ 15 desired</td>
</tr>
<tr>
<td>(upland farms)</td>
<td></td>
<td></td>
<td></td>
<td>≤ 15 during operation</td>
<td></td>
</tr>
</tbody>
</table>

7.3.4 **Favourable meteorological conditions for infection and spread of ergot (Claviceps microcephala) on field millet**

Siddiqui and Khan (1973) noted that the conditions most favourable for this disease were:

- mean temperature between 18–20°C and 28–30°C;
- mean relative humidity about 90 per cent;
- light showers every day for 5 to 6 days during anthesis.
7.4 Application to operational crop protection

Forecasts of meteorological conditions favouring disease and pest development may be either general, or in the form of numerical values of specific weather elements. They can be used for:

- Predicting the time or progress and severity of outbreaks, so allowing rational control measures to be initiated: a double forecast is required, first predicting the environment, and then the effect of this environment on the disease or pest;

- Providing operational advice on the timing of chemical applications or other countermeasures: this is likely to be one of the most important uses for weather forecasts since it should lead to improved benefit/cost ratios, minimize environmental pollution, and slow down the development of resistance to pesticide in the organisms being controlled.

Applications of weather forecasts in these areas are still in their infancy in most countries. The following few examples are intended to demonstrate a few of the many possible applications.

7.4.1 Example of broad requirements for plant protection

Hrbek (1983) states that in Czechoslovakia the following forecasts for plant protection are those most often required from the National Meteorological Centre:

- Forecasts for several hours ahead up to 24 hours ahead of wind speed, rainfall (time and amount), late and early season frosts, temperatures over 22°C, fog, low cloud, visibility, near-ground turbulence, wind direction;

- Forecasts up to several days ahead of maximum and minimum temperature, rainfall and snow;

- Special forecasts for pest and disease development (e.g. potato blight).

7.4.2 Short-range warnings

These are based on current weather data and very short to short-range weather forecasts

- Example of forecast for Peanut Leafblotch disease: "Peanut fields will continue to be wet from rain for long periods during the next 36 hours. Combined with warm night-time temperatures, rapid increases of peanut leafspot are possible where fungicides have not been used";

- Meteorological conditions for the transport of spores and outbreaks of Blue Mould Tobacco disease in Southern Ontario. If the critical flux density of conidia in a region has been reached, air trajectory forecasts, and synoptic and mesoscale forecasts of precipitation will determine in near real time the potential for the spread of Blue Mould disease;
• Example of forecast for apple scab infection: "During the past 24 hours there have been 8 hours of wet vegetation with a mean temperature of 16°C. During the next 24 hours, ten hours of wetting by rain are expected, with a mean temperature of about 16°C. These combined wetting periods will produce a light to moderate apple scab infection period. Growers should be prepared to commence spraying tomorrow to prevent the development and spread of scab".

7.4.3 Medium-range warnings

These are based on recent and current weather data, and medium-range forecasts.

• Examples of forecast/warnings for week commencing 18 June 1984: "The present close and warm conditions with some rain and drizzle on Tuesday will give way to fresher and brighter conditions for Wednesday and Thursday. Further close, cloudy weather will develop over Friday and Saturday, and unsettled conditions will continue over the weekend with small amounts of rain. This weather will continue to be suitable for Rhynchosporium and to a limited extent Septoria: mildew will still occur in the south and east".

• Occurrence of Sclerotinia sclerotiorum of sunflower heads: Nouallet (1981) has found three "weather types" defining conditions likely to lead to infection in France. One of these types is illustrated in Figure 7.1. A forecast of such conditions 48 to 72 hours ahead could allow operational effective control at lesser cost.

• A weather-timed scheme for fungicide applications. Gillespie and Sutton (1979) developed a predictive scheme to improve efficiency of fungicide use in management of alternaria leaf blight in carrots, so that fungicide was applied only when weather forecast over the next thirty-six hours was favourable for infection of carrot by Alternaria dauci. Favorability of weather was based on temperature forecast regionally, and duration of leaf wetness predicted according to occurrence of rain and regional forecasts of cloud cover and surface wind speed (see section 7.3.2). The disease was controlled effectively even though there were two or three applications less than used in regular spraying.

7.4.4 Long-range warnings

These are based on observed data, cumulative conditions or climatological statistics.

• Cotton Leaf Worm: In Egypt, Hosny and Iss-Hak (1967) demonstrated that the daily average temperature, daily minimum temperature and average soil temperature at 5 cm depth during the critical period (between 11 February and 10 April) were responsible together for about 90 per cent of the annual variation in egg-mass numbers. The results can help to foresee potential outbreaks early enough to prepare for insect control.
Figure 7.1 Type of meteorological situations leading to infection of sunflower by *Sclerotinia sclerotiorum* (after Nouallet, 1981)

- **European Corn Borer (Ostrinia nubilalis):** Arbuthnot (1949) used data from Europe and Asia to produce a graphical relationship between mean annual rainfall and temperature, and the number of generations of the insect. From this he deduced the most likely reaction of the European Corn Borer to environments prevailing in USA (where the insect was already a serious pest of maize), to assist in organizing the best research and control programme to combat it.

- **Weather-based control of Coffee Leaf Rusts:** According to Nutman and Roberts (1970), dispersal of the uredospores of the coffee rust pathogen by rain is extremely short-range, and generally takes place within an individual tree. Movement of
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inoculum is virtually impossible until after the first "dispersal shower" of the rainy season, i.e. over 7.5 mm. The heavier this dispersal shower, the more effective the spore re-distribution.

- In parts of east Africa where it is possible to forecast the probable date of this shower with reasonable accuracy, there is a period of approximately three weeks during which a spray with a copper fungicide provides effective control.

7.4.5 Forecasts for application of agricultural chemicals

- Example: "The risk of wash-off and winds over ten miles an hour during Friday give unfavourable conditions for applying agricultural chemicals";

- Example: "Wind speeds are expected to be mostly favourable for application of agrochemicals today and tomorrow. Winds will be variable in direction, 2 to 4 m s⁻¹ today becoming southerly 3 to 5 m s⁻¹ during late afternoon. Temperatures are likely to exceed 27°C tomorrow so caution should be exercised in applying oil-based sprays".

7.5 Concluding remarks

Many of the applications of weather forecasts to crop protection are relatively straightforward, and can be exploited with existing knowledge. However, in numerous other cases the full value of forecasts will not be obtained until the relationships between pest and disease development, and weather are better understood. Even then the maximum benefits will not be achieved in operational crop protection unless the meteorological forecasters, plant pathologists and entomologists not only collaborate closely in setting up and maintaining warning schemes, but also ensure that the end product takes full account of the demands of the crop production systems being used by farmers and growers.
REFERENCES


CHAPTER 8

THE PRODUCTION AND DISSEMINATION OF AGROMETEOROLOGICALLY-
BASED INFORMATION AND WARNINGS FOR PEST AND DISEASE CONTROL

8.1 INTRODUCTION

Useful agrometeorologically-based information, advice, and warnings for crop protection can now be produced successfully by many countries. Much more remains to be done to extend the advice in order to cover more crop diseases and pests in further areas. At present, the main problems are to improve the agrometeorologically-based information and to transmit the advice to the users in good time. These problems exist worldwide.

The methods of production of such information and warnings differ for various countries and for different crops diseases and pests. Even in the same country, there are different levels of professional and operational activity. This chapter analyzes methods and trends worldwide for the preparation of information and warnings in their various stages. A specific analysis was made for the various climatic parameters involved. At present, many countries still do not make use of available agrometeorological information for crop protection. Where such information is used, it is often under-exploited, leaving much room for improvement.

This chapter deals with dissemination methods, including both conventional and advanced technologies available in the world today.

Answers to a WMO questionnaire (Appendix 8.1) were used as a basis for this chapter. The sixty-eight participating countries spanned different regions and continents. The answers in many cases included extensive literature and numerous examples, that helped to give a better understanding of progress and trends in the vital area of information and warnings for crop protection. The countries were divided on the basis of the questionnaire into three groups (Appendix 8.2) according to the extent of their activities in this field of study.

8.1.1 Production of warnings and information

8.1.1.1 Types of information to be disseminated

Operational crop protection advice includes three types of information:

1. Instruction and information, without using meteorological data.
2. Information using current weather.
3. Information using both current and forecast data.

The two latter types can be subdivided according to whether the meteorological content is pure weather information, or is agrometeorological in character. It must also be remembered that the information given to advisers is usually different from that passed to farmers because the questions which farmers and advisors raise are not the same.
8.1.1.2 **Types of forecasts**

These are chiefly:

1. Prediction of the first date of disease or pest attack, according to weather conditions, with or without field observations.

2. Intensity and duration of pest and disease attacks.

3. Negative forecasts - i.e. length of the period free from pests and diseases.

4. Weather conditions associated with the necessary treatments.

8.1.1.3 **Instructions for treatments**

These are in the form of "when to spray" or "when not to spray": they usually include advice on the required concentration and amount of pesticide, frequency of application, and sometimes the costs also.

8.1.2 **Methods of dissemination**

There are simple traditional methods for transferring information and advice, such as personal contact and extension services, bulletins, etc. These are accepted in most countries, and in the developing countries are usually the only methods used, as few sophisticated methods are employed.

Some agricultural systems do little at present to encourage expenditure on improving methods of dissemination. In the cereal growing sector of Western Europe, for example, for which the Common Agricultural Policy at present sets high support prices, there is often little penalty in "insurance" farming where pesticides (e.g. herbicides, fungicides, insecticides) are routinely applied according to calendar or crop development. In this case there may be little incentive for adopting more rational pest- and disease-control strategies.

In some countries, where agriculture contributes only a small amount to the gross national product, radio and television time for the dissemination of information pertaining to crop protection is simply not made available. Paradoxically, much poorer countries often have a good radio dissemination system available.

There are rapid developments in "information technology" that are beginning to provide ways for the fast and cheap supply of highly specialized data. It is ironic that expansion of such methods has in many cases been for the most trivial reasons, for example the introduction of cable television in order to offer a wider choice of low quality television programmes to the viewer. In general the cost and complexity of information technology systems make them inappropriate at present for poorer countries.
8.1.3 Types of users of the information

The users of the information are a broad range of public and private enterprises. These include farmers, advisers on plant protection, chemical, fertilizer and seed companies as well as the media, commercial organizations, research stations and universities.

8.2 AGROMETEOROLOGY AND THE INFORMATION SYSTEMS

Most information systems in European, South American and Eastern Mediterranean countries make use of agrometeorological data. The information is usually published weekly, some year-round and others through the critical periods. Most of the European and some Group 1 and 2 countries (Appendix 8.2) use agrometeorological information for warnings, as in Kenya, apparently the only African country to do so at present.

8.2.1 Organization of the systems

Crop protection warning systems are primarily under the jurisdiction of crop protection centres, agricultural institutes or national weather services. In some countries (UK and Austria for example) commercial organizations and research bodies also contribute to the information systems. Some countries, such as Switzerland and Colombia, issue warnings directly to the public through their weather services.

There are numerous exceptions in the organizational apparatus. In Costa Rica, for example, the Growers Organizations, such as the National Banana Association, take an active part in the maintenance of the crop warning system; in Malaysia, the Oil Palm Growers Company performs a similar function. Another type of organization is the example of the Federal Republic of Germany, where regional agrometeorological centres have been established and staffed with weather forecasters, agrometeorologists, agronomists, plant pathologists, etc. These centres issue the agrometeorologically-based products directly to farmers.

In Mali the National Meteorological Service is not directly associated in the process but in the United States, however, offices of weather prediction for agriculture, staffed mostly by professionals, provide advice using data that in most countries are normally limited to weather services.

In Australia, only the national meteorological service analyses the data and issues advice. Other agencies use its means of telecommunication.

The British Meteorological Office issues warnings based on empirical relationships connecting weather and disease development, using predicted as well as current weather. Warnings are issued for seven important fungal diseases. (The main climatic elements used here in assessing disease risk are temperature, humidity, rainfall and wind speed).

8.2.2 Meteorological services and the crop warning schemes

Countries may be classified according to the following categories:

- The Meteorological service provides the warnings with or without formal liaison with other bodies;
National weather services limit their contribution to the preparation of meteorological information. This information is usually transferred to the extension or specialized plant protection services for analysis and interpretation and the issuing of the appropriate advisory information.

Combined teams of meteorologists and phytopathologists, entomologists etc. provide warnings.

In all three methods, the published products make use of meteorological data.

8.2.3 Range of crop diseases and pests included in the systems

Throughout the world, there are various information and warning systems for a wide range of crops. The most common are: (see Appendices 8.3 and 8.4)

1. Vegetables - potato, tomato, cabbage, beans.
2. Fruit trees - apples, pears, cherries, peaches, apricots, bananas, olives, grape vines, citrus, cocoa, mango, papaya.
3. Cereals - wheat, oats, barley, maize, rice, sorghum, millet.
4. Industrial crops - cotton, sugar beet, sugar cane, soya beans
5. Ornamental crops.

8.3 Examples of warnings and information bulletins to different countries

Some of the results from the survey are summarized in Appendix 8.5, which gives a list of meteorological variables used in different countries to produce warnings and information bulletins for various diseases and pests: the tabulations are given separately for the following crops: potato (late blight only); wheat and other cereals; maize; fruit (excluding grapes); grapes; vegetables (excluding potato).

The selection of meteorological variables differs from country to country, but certain variables emerge as the most common. For most diseases and pests it is noted that a greater emphasis is placed on producing analyses rather than forecasts of likely pathogen progress, indicating that more information bulletins are provided than forecasts.

Potato late blight (Phytophthora infestans) is the main focus in many countries of their warning and information systems. This is so in European countries, as well as Japan, Canada, Cyprus and Kenya. In France, the Netherlands and Japan their products also include forecasts. Little use however, is made of hourly meteorological data as compared with means and extremes.
CHAPTER 8

Most of the warnings are given for the first attack of a specific disease or pest or for the first necessary treatment. For example, Czechoslovakia, Greece and Italy issue warnings when meteorological factors such as temperature, rainfall and humidity reach threshold values. The growers are instructed to continue and intensify the control whenever the disease or pest appears, and favourable meteorological conditions persist. This active reporting system is preferred over the negative systems that exist in some countries that limit themselves to providing information on periods free of pests and diseases. This same service is provided in the UK implicitly by issuing an advisory against spraying for pests when the likelihood of an attack is negligible.

Forecasts for the first attack of Phytophthora are given in Canada, Australia, China and the UK. In the United States, the first signs of the disease are detected by field workers' observations which result in alerts that conditions are favourable for the development of different pests and diseases. In Quebec, however, negative forecasts are made to avoid the application of control measures when meteorological conditions are unfavourable for the development of disease.

Disease and pest intensity are included in the warnings issued by several countries. In France, for example, an analysis is made of samples taken, and traps (pheromone, baited, or light) are used during risk periods, with this information permitting some advice on likely intensity. The Netherlands include intensity in their warnings for pests or diseases of potato, maize, cereal crops and fruit. In the UK, indications of intensity using simple models and meteorological data are also given for hop downy mildew, apple scab, Rhynchosporium, net blotch, barley mildew, eyespot, potato blight, and fire blight. Czechoslovakia also issues warnings on the intensity of apple scab. In the Federal Republic of Germany, disease and pest intensity is obtained from a combination of model outputs and observed biological information contributed by special staff members attached to the Plant Protection Service. Poland also includes intensity in warnings.

A number of countries outside Europe also issue warnings of disease and pest intensity. In Canada, for example, some warnings are given in terms of a "Corn Borer Index" and spraying advisory bulletins are issued to apple growers on the codling moth and other apple pests. In Quebec meteorological data are used to indicate likely disease intensity for potato blight, apple scab and grey mould, and the population size of the European corn borer based on conditions during the egg-laying period. In some cases, of course, warnings are issued solely on the basis of disease and pest monitoring in the field, and require no operational meteorological data: in these cases any large departure of meteorological conditions from climatological normals during the warning period may produce substantial errors in the predictions.

A few countries include expected duration of disease in their warnings. These forecasts are based on weather predictions in countries such as New Zealand, Portugal and Malawi, for as long as the crop is in its vulnerable stage. Ireland and Zambia also deal with the matter of expected duration, but in a general way. Examples, for potato blight warnings from Ireland, are:

- "The weather over the next few days will be conducive to the spread of potato blight, especially in the west and north-west. Weather conditions suitable for spraying will occur this afternoon and before noon tomorrow".
- "Conditions favourable to the spread of potato blight are expected at times over the next 3-5 days, especially in the western half of the country. The weather today and tomorrow should be suitable for spraying".

- "Weather conditions favourable to the spread of potato blight will occur at intervals during the week. Spells of three hours or more with good drying will occur at times".

The forecast material may be presented in verbal, numerical or graphical forms. Products also include maps. For example, the Federal Republic of Germany issues maps indicating the negative forecast for Phytophthora infestans (Figure 8.1).

Figure 8.1 Negative forecasting for outbreaks of Phytophthora infestans in West Germany: number of days between 16 April and 7 May 1984 with no risk of an outbreak
8.4 METHODS OF DISSEMINATION

8.4.1 Personal contact

Personal contact between farmers and advisers is an accepted method for dissemination of crop protection information. This method is particularly effective in close-knit communities where farmers are in touch with the person in charge of disseminating the information. The high cost of such a service, due to its low user/producer ratio makes it impossible for the same person to generate the information. Still, it must be seen as the only effective means of communication in countries lacking telephone or broadcasting networks, or in countries where the information services are saturated when the services cannot even cope with one disease or pest because of the local variations in pest and disease development.

If the final link in the chain is to be a human one, the person disseminating the information must be skilled in transmitting warnings to non-experts in pest and disease control. He must also be well-trained to undertake some of the background work related to the advice he gives; this last may be costly to achieve.

Personal contact is a useful complementary method to other methods of dissemination. Though such a service cannot be given on a mass basis, it is useful to provide explanations and clarifications.

In most countries, personal contact comes under the auspices of the Ministry of Agriculture, and in about one third the Meteorological Services as well. In Switzerland and Columbia, the service is exclusively under the jurisdiction of the Meteorological service. Ten per cent of the countries involved in the survey do not have any such service. These include Japan, UK, Austria, Italy, Greece and Zambia.

8.4.2 Postal services

There are two main types of postal advisories:

1. Regular bulletins which include meteorological data and/or a summary of agrometeorological information, mostly including crop protection.

2. Specific ad hoc bulletins that include warnings and guidance products.

In most of the countries that publish bulletins, the products include information on past weather and a summary on the general agricultural situation. Some of the products include information on pests and disease, but such information is not given operationally. Operational bulletins are generally more effective as a guide to the farmer and adviser. This type includes urgent, practical operational material and explanations, articles, and so forth. The farmer can refer to the information the following year. This method can be efficient if the information is clear, precise and produced quickly.

The great advantage of postal products is the large amount of data that can be included in each bulletin or message. A ten-day summary, forecast data, instructions for protection and explanations on materials, etc. can be summarized in a report. However, one must expect a delay of at least a few
days for the information to reach the farming community, which explains why this method helps in planning rather than providing a genuine operational service, with the exception of the French "SPV".

The "Avertissement Agricole SPV" is published in France by three different agricultural branches, on a regional basis, and is designed to be operational. The delay in the post is minimal -- about 24 hours. The analysis of the material takes eight hours so the total delay is also minimal. The product includes basic technical material, forecasts, recommended material for use, frequency of spraying, prices of materials, licence for sellers, and any other necessary information. It also covers the educational aspect of this particular subject, in order to encourage an intelligent approach from the grower to the problem of operational crop protection. This information sent by post complements warnings and flash information displayed by the media.

Approximately half the countries use postal services as a method to disseminate information. Most European countries do but not so many African and Middle Eastern countries employ this method.

8.4.3 The press

The press is a useful, cheap and quick method of dissemination of information. About 60 per cent of the countries make use of newspapers for this purpose. Countries not doing so at present include Canada, UK, Denmark, Switzerland, Austria, Japan, Hong Kong, Singapore, Turkey, Syria and Iraq and several in Africa.

8.4.4 Telephone

Potentially there are three different ways of using a telephone as a means of issuing guidance and warnings for crop protection.

1. When the farmer calls the adviser directly for information and guidance.

2. When the farmer listens to a recorded message on a tape loop.

3. When the disseminator makes a call to the farmer. The method is direct, cheap and fast with a quick dissemination of information.

The telephone is used as a method of dissemination of crop protection information and warnings in about half of the surveyed countries. The number is much higher for the developed countries. In most of these countries, one can apply directly by phone to the crop protection service or to a fixed telephone number for a pre-recorded message.

The "farmer-to-adviser" is obviously a desirable method, but the number of successful connections is limited during critical periods. In countries where the farmers are capable of understanding the significance of weather, calls to the forecast centre provide information that may be used in the field. Where the farmers' skills are lacking, calls to advisers in extension services are useful. Here again, the number of phone contacts are limited. The recorded message can provide clear instructions for treatments as required. In another arrangement, the farmer receives a regular and special service from the forecaster for a fixed fee (via an ex-directory number). When lines are overloaded, the farmer can call the Meteorological Service and get the regular public forecast. Similarly the farmer can contact
his state-run agricultural advisory service for advice on crop protection (which may be based in part on agrometeorological inputs): again, though the agricultural adviser is often difficult to contact, the taped message may be sufficient for the progressive farmer, and need be updated only when necessary. The second case is chiefly one of a regular liaison between a specific farming community and a specialized agricultural adviser. The services include a complete package of information with advice on crop protection.

In many countries, the telephone is used as a method for issuing the warning. For example, there are recorded weather forecasts available from some meteorological and agricultural offices by telephone responder or "code-a-phone": the code-a-phone service in Canada, updated several times daily, has proved to be very popular.

In several countries, separate channels are available from the meteorological and extension services. In general, the telephone has proved to be a swift and relatively inexpensive means of disseminating products in many countries. Italy and Ireland have telephone responders only in the meteorological service; China has such a service in the crop protection centre and the meteorological service. France has all the above-mentioned facilities. Japan and European countries such as Denmark, the Netherlands, Sweden, UK, and the Democratic Republic and Federal Republic of Germany have recordings. Austria and Switzerland have recordings and telephone communication to their crop protection centres. Australia, Canada, China, Czechoslovakia and Poland have telephones to their crop protection institutes.

8.4.5 Radio

Radio receivers are commonplace everywhere and are cheap and portable. Routine and specialized programmes of interest to the farming community are available in most countries. In developed countries, products are given in programmes broadcast at convenient times of the day for farmers to tune in. In developing countries, a greater share of the broadcast time is available for agricultural purposes, reflecting the fact that farming constitutes a more important sector of the national economy. About 85 per cent of the surveyed countries reported that radio is used to disseminate crop protection information and warnings. In a country such as Ireland, the radio is a vital means of issuing blight warnings. Warnings are carried on the national weather service during the regular news broadcasts at 13:30 and 18:30. The Central Analysis and Forecast Office (C.A.F.O.) also includes advisories on their regular live radio programme using regular forecasts. In Canada similar products are available in the eastern provinces, and have proved to be most popular. Coverage is almost complete in the Atlantic region. The "Farm Weather Forecast" was evaluated by a specific committee in 1983. The findings suggested that about 75 per cent of the respondents listened regularly and over 90 per cent considered the broadcast a useful addition to the regular public broadcast. Perhaps the most useful information coming out of the survey was that 73 per cent of the respondents obtained the forecast from a commercial radio station, whilst only 18 per cent from Weatheradio, which is broadcast on a dedicated frequency outside the normal AM/FM bands.

The results of the survey in Newfoundland indicated that 70 per cent received the broadcast on regular radio, 10 per cent by Weatheradio, and 20 per cent by cable television. The latter is a convenient form of
Weatheradio which indicates a 30 per cent combined use. Furthermore, 70 per cent of the respondents considered the "Farm Weather Forecast" more useful than the public forecast.

Overall, the "Farm Weather Forecast" was seen as a valuable product but which could be improved by more timely dissemination and perhaps better management of the contents and advice on how to use them operationally. One very useful piece of information from the survey was that more effort was required to increase the awareness of Weatheradio within the farming community. Those who used it, liked it.

In Nova Scotia, apple scab advice and potato blight forecasts were distributed on a regular radio network in the Annapolis Valley. In Alberta public forecasts generally satisfied the farming community's needs. In 1983, however, an experimental agricultural forecast of general weather information, relative humidity and drying index was broadcast on Weatheradio from Edmonton and is planned to expand the service to Calgary. Ontario Weather Centre (OWC) relies on the broadcasting services to distribute many of its forecast products; however, a large number of radio stations supplied with these products are unable at present to accommodate forecasts tailored to particular user-groups.

Users of weather information who have a special interest in the weather may receive this information anytime on Weatheradio Canada. Weatheradio operates a station in the Toronto area owned by Environment Canada's Atmospheric Environment Service. The station transmits weather information continuously, around the clock, seven days a week. It transmits a range of weather information tailored to the interests and needs of local users. This regular programme is repeated and updated at regular intervals. The length of the programme cycle is typically 5-8 minutes, and normally includes current weather forecasts, synopses, extended forecasts and special weather information for agriculture.

In the United States, most of the forecasts are received from wire services such as Reuters, Associated Press etc. and are analyzed by radio and television stations. A number of radio stations have a specific continuous weather channel. Warnings are generally issued on a weekly basis and if necessary daily.

Radio products are disseminated daily in Australia except for weekends and holiday periods. An important epidemic would be included in a regular news summary and repeated 3 or 4 times daily. Any warning issued from the bureau of meteorology becomes an adjunct to the news bulletin on radio.

In general, most of the developed countries are using radio to transmit information on warnings on crop protection whenever the need is justified. In addition, some countries of all groups are using radio for this purpose on a regular basis: Bangladesh — fortnightly; Czechoslovakia — weekly; Greece — daily (when necessary); Hong Kong on a regular basis; Italy — weekly or twice weekly; Saudi Arabia — daily; UK — weekly; Yugoslavia — weekly.

### 8.4.6 Television

Television is obviously an effective medium to issue weather and agricultural advisory products and is used as a disseminating medium in about half the countries in the world. A typical product is the general forecast
given once or twice a day. In some western countries, weekly forecasts are given.

In the United States, weekly forecasts are available in particular areas depending on the season and agricultural interest. During the growing season, many television stations carry daily programmes with updates two or three times a day. Some stations employ their own forecasters. In Australia, an important epidemic would form part of the news bulletin and would be repeated three or four times daily. Any warning issued from the Bureau of Meteorology becomes an adjunct to the televised news bulletin.

In the Netherlands and France, television is used on occasion to issue warnings. In Britain, however, the only news bulletin of interest to farmers is a seven-day forecast of general weather conditions with a brief mid-week update. In Ireland, blight warnings are broadcast on the day of issue with the weather segment of the nightly televised news summary.

In some countries, television is used as a method of dissemination of crop protection information and warnings on a regular basis, for example, Czechoslovakia three times a week, and Saudi Arabia once a week. Most of the other countries in North and Central Europe use it when necessary. Still, many countries in the developed world do not use television for this purpose.

It must be recognized that in some countries where these services are provided, farmers are sometimes unable to afford television sets. In other cases the signals may be too weak in remote areas to be received.

8.4.7 New technology: Videotex and Teletext

The first Videotex system was British Telecom's PRESTEL, introduced in 1979. This is a computer-based information service which may be accessed via public telephone lines to provide frames of information that are then displayed on a modified television receiver. The computer holds more than $10^5$ frames of data. PRESTEL contains a considerable amount of information of interest to farmers, including some disease and pest control advice. Information sources providing data to PRESTEL include the Ministry of Agriculture, the Meteorological Office, agrochemical and agricultural machinery companies, and many others such as travel agents, airlines and banks.

Superiority of this type of system over other methods of dissemination is due to the following:

1. Information retrieval is instantaneous, giving up-to-date products to the user.

2. Information retrieval is concise, obviating the need to sift through numerous reports, studies and manufacturers' literature.

3. The system is interactive, allowing users to have a direct line to the specific information sources. For example, one can request literature from a particular information provider or request details from a particular source in addition to those contained in the PRESTEL data-bank.

No special skills are required to interact with the system, which is designed to achieve simplicity by using advanced technology. Some PRESTEL products
are free, whilst others bear a charge, depending on the users' requests. This is an important development which holds great promise in the present context.

Variations on this system include semi-private systems (closed-user groups), where only authorized subscribers can retrieve information. There are also completely private schemes outside the national framework. The UK Meteorological Office is already providing information of a general meteorological nature to both open and closed PRESTEL schemes.

From the point of view of an organization like the Meteorological Office, where government policy states that the service should operate commercially as much as possible, the advantages are considerable once enough people have sets connected into the system. The number of these sets is about fifty thousand today and is increasing rapidly. There is an automatic charge when a page is accessed. This charge can be small - as little as a few pennies for each access.

Apart from the revenue-gathering aspects, what matters is that this method offers a means of providing any user with instantly available, specialized, agrometeorologically-based information. It can be updated regularly and automatically by computer-to-computer links using the PRESTEL communications system. Regrettably, one cannot foresee this method being introduced into less-developed countries for a considerable time.

Videotex is operational or is being introduced at present in a number of countries, but only 15 per cent of the countries surveyed have this technology: they include Canada, France, the Netherlands, Sweden, and the United States, in addition to the UK.

Teletext is additional information broadcast after multiplexing with the standard television channel transmissions and is received by using a modified set. The number of frames of information that can be carried in this way are only around $10^3$ at present, and they are transmitted sequentially, so that there is usually some delay in displaying the required frame of information. However, developments will allow a substantial increase in the amount of transmitted information and more rapid interrogation, and Teletext will then offer a very effective method of passing operational crop protection information to farmers.

8.4.8 Telex and methods using computer-to-computer links

These methods refer in particular to the transfer of meteorological information from a national meteorological service or regional weather centre to organizations that interpret the information before issuing advisory information to the farmer by whatever method is available. It is important to note that almost direct computer-to-computer linkage can be made by telex managers connected to each computer and then automatically passing or receiving telex messages.

A number of countries use telex to pass agrometeorologically-based information between various organizations. In some cases telex is employed to pass warnings to individual farmers on a repayment basis: in Australia for example the Bureau of Meteorology employs this method, but via a business agency telex which then phones the information to the farm (the Bureau has insufficient staff to disseminate the warnings by telephone).
8.5 EXAMPLES OF SYSTEMS FROM THE UNITED KINGDOM AND USA

8.5.1 United Kingdom

In an operational system described by Roe (1984), a number of computer programs incorporating relations between weather and plant disease have been written, the first being for barley mildew in 1975. The programs are mostly run about mid-morning every day during the season, accessing data from the previous 24 hours that have been passed into the synoptic data bank from stations throughout the United Kingdom. Output from the programs is in the form of a telex message dispatched to the Ministry of Agriculture, Fisheries and Food (MAFF) computer at Guildford about midday for subsequent access by the Advisory Service plant pathologists in each region. The data are also sent direct to the Crop Pest and Plant Disease Intelligence Unit at Bristol for interpretation (see Figure 8.2). Certain routine messages are similarly telexed direct from Bracknell to the East of Scotland College of Agriculture and to the Department of Agriculture, Northern Ireland.

![Flowchart of weather information flow](image)

**Figure 8.2** Flow of weather information to and from the Crop Pest and Plant Disease Intelligence Unit at Bristol (MCC — Meteorological Communications Channel)

In 1983 the system was simplified with the introduction of HERDS, a plant disease message incorporating the most useful information from each of the four existing disease messages.
A shortened version of the telex output is shown in Figure 8.3, which includes a description of the information sent out. The full message contains data for almost 100 stations in the United Kingdom, of which about 55 report hourly and can be used to derive the full complement of disease indices.

The HERDS program runs at about 1045 GMT, by which time four other programs producing the component data have already run. The steps involved are shown in Figure 8.4. Output from HERDS is directed to an on-line dataset which is then accessed by communications computers that dispatch the message to recipients with the aid of a telex manager.

8.5.2 United States

Croft et al. (1976) describe a computer-based disease management system consisting of a central computer (at Michigan State University) with appropriate software, and a telecommunications network linking extension service offices over a wide area. At these sites, remote data terminals are used to update and interrogate a large database associated with on-line disease and pest management. The system was developed initially for the apple but has been extended to include other crops.

The personnel and the principal information flows associated with pest and disease management in Michigan agriculture are shown in Figure 6.3. They extend from the research base where programs are initially designed and experimentally evaluated, to the within-field level where various para-professional and disease pest managers apply the science. As can be seen from Fig. 6.3, regional pest management (the portion above the dashed line) is viewed as the responsibility of the existing state-federal extension service. However, within-field management is a private sector responsibility associated with those personnel listed below the dashed line.

8.6 ADMINISTRATIVE ASPECTS OF CROP PROTECTION SYSTEMS

8.6.1 Organizations distributing crop protection information and warnings

There are in general three ways in which authorities in various countries distribute the material. There are:

1. Governmental - The plant protection service attached to the Ministry of Agriculture is the primary distribution source, sometimes in collaboration with the meteorological services, as in China and Ireland. In many countries, this is the only method of distribution.

2. Educational and technical institutes, as in Canada and the UK. Some specific examples are: Austria - Sugar Research Institute; Denmark - the Research Centre for Plant Production and Agricultural Advisory Centre; Sweden - the Swedish University of Agricultural Sciences (in addition to governmental); in Mauritius, the Sugar Industry Research Institute (in addition to governmental). In Malaysia, this is the only active category.

3. Private companies - these include chemical companies, as in the UK and Zambia; crop consultants, as in the UK; Growers' associations such as the Seed Potato Growers' Association in Austria; in Mozambique, a pesticide company; in Zambia, Agricultural Marketing Boards. In some countries, such as Fiji and Singapore, primary industries are involved.
### Figure 8.3 An extract from a HERDS telex message

1. **STN NO.:** The station identification code.
2. **APPLE:** The apple scab index.
   - A — indicates that the requirements for at least light infection have occurred.
   - NM — a "near miss". The criteria for light infection were not quite satisfied.
   - / — conditions unsuitable for infection
3. **RHYNC:** The *Rhynchosporium* index. R1, R2 and R3 indicate that conditions suitable for slight, moderate or severe infection occurred respectively. (It takes the same meaning as before.)
4. **SEPTO:** The Septoria index. The symbol S indicates the possibility of Septoria infection.
5. **NETBL:** The net blotch index. 0, 1, 2 or 3 may appear, where 3 indicates the highest risk of infection.
6. **RAIN:** The total rain (millimetres) over the rainfall day (+0.0 indicates trace).
7. **09DPD:** The 0900 GMT dew-point depression (°C) on the day of the message.
8. **BARLEY MILDEW:** Two indices are calculated:
   - **SMITH** — The Smith index involves the combination of several relevant weather variables.
   - **POL** — The Polley index. The scale 0, 1, 2 or 3 is used to indicate an increasing risk.
9. **EYESPOT:** WD is a measure of the infection risk. Again threshold values are significant.
10. **POTATO BLIGHT MODEL:** Several variables are derived:
    - **SM** — The Smith period calls for suitable weather on two successive days.
    - **SR** — The indicator P (partial) in the daily weather bulletins is used to show weather consistent with disease build-up. NM indicates a near miss. / indicates criterion not met.
    - **AIN** — a measure of the accumulated infection
11. **WET PERIODS:**
    - Certain plant diseases require an obligatory period of leaf wetness for part of their life cycle.
    - **TIME OF END** — the time of end of the wet period to the nearest hour. '00' signifies a period ending at midnight and 'C' a period continuing into the next day's message.
    - **LEN** — duration (length) of wet period in hours. This observation accumulates continuously wet periods over several days if necessary.
    - **MEAN TEMP** — the average temperature (°C) for the wet period.
8.6.2 Charges for services

Services are provided free of charge in many countries. This is particularly true in east European, African, Middle Eastern and North and South American countries. In Western European countries, charges are often levied, as in Ireland and the UK for telex services. In Australia, Canada and New Zealand there are also charges for telexed information. In the Federal Republic of Germany and France levies are made for bulletins and personal contacts. There are similar charges for bulletins in Austria, the Netherlands and Sweden. Telephone calls are charged in Bangladesh and Finland.

8.6.3 Delay in getting operational written bulletins to the user

The delay varies between different groups of countries. In most of the developed countries, the delay is 1-2 days and this is also the case in Bangladesh and Libya. In Kenya the delay is typically 3 days, and is generally longer in most of the developing countries.

8.7 ASSESSMENT OF DISSEMINATION METHODS

The survey shows that most countries (62 per cent) select radio as the most satisfactory dissemination medium. This method is fast, cheap, and is available with wide distribution. The percentage is even higher (72 per cent) for groups 2 and 3. Views on personal contact differed between the developed and other countries. This method is judged satisfactory (91 per cent) by developing countries, whilst the developed countries rely more on high technologies.
The third method judged satisfactory is the telephone, especially by the developed countries but only 20 per cent of the developing countries gave a satisfactory rating, probably because of insufficient lines and attendant technologies. Where television is available to disseminate material, it was selected as a satisfactory medium, in particular better than the press. Post was considered satisfactory by only 12 per cent of the respondents. The reason is probably the delay in arrival of the material.

There are other satisfactory methods in use such as telex, code-a-phone, videotex and teletext, but in most cases these are employed for crop protection purposes in only a limited number of developed countries at present.

8.8 TRAINING AND EDUCATIONAL METHODS FOR CROP PROTECTION

Many countries have training and educational programmes for advisers and farmers. These include workshops and refresher courses, as in Canada, Czechoslovakia, Democratic Republic of Germany, France, Israel, and Yugoslavia, for example. In Quebec, there are programmes for advisers and extension specialists on crop protection. In France, these programmes are organized by Technical and Educational Institutes, the Ministry of Agriculture and Agricultural Institutes. In the UK, there are training programmes for advisers organized by extension services, and chemical companies provide training for their own representatives, farmers and crop consultants. In Finland and Sweden, universities provide programmes for advisers. In Japan a four-day course for advisers is organized regularly for about 100 participants from the various growing districts. At the prefecture level, the concerned people are given one to two days training regularly. In a number of countries, seminars are organized by the Ministry of Agriculture for advisers. Cyprus, for example, has a training and educational programme run by the extension service for farmers. In Israel, the Ministry of Agriculture, regional committees and growers' organizations are responsible for various types of professional training. In Egypt, seminars and training sessions are organized for new graduates.

In Kenya, the administrative officer calls a public meeting and informs the farmers how to protect their crops when pests and diseases adversely affect a particular area. This is done according to guidelines laid down by the Crop Protection Service.

Cameroon has a regional phyto-sanitary training centre which trains officials of different levels in crop protection. Farmers are trained in rural centres and there is also a special training centre for young farmers. In Gambia there are model farms and farmers (usually very innovative) to extend crop protection information to other farmers by in-field demonstrations.

In general, most countries have training programmes, specific courses, seminars, information sessions and field demonstrations, mostly during periods when the farming community is not preoccupied with crop production. The few examples given above provide no more than an indication of the large effort across the world devoted to training.

It is probably true to say that most training courses in crop protection include grossly inadequate information on the pertinent aspects of
agrometeorology which largely reflects the scant knowledge in this area of many pests and disease. As this knowledge increases it is clearly very important that it should pass as rapidly as possible to advisers and farmers whenever the opportunity occurs.

8.9 LOOKING TO THE FUTURE

8.9.1 Plans for improving warning schemes

The trend in developed countries is to improve warning schemes by making more effective use of agrometeorological information through the introduction of more synoptic stations and by making better use of meteorological observations and forecasts. Developed countries are introducing numerical simulation models of pests and diseases based upon ecosystem and bioclimatic models. One interesting development is that of Portugal which has made a very exceptional recommendation that biological control and treatments should be considered in consultation and liaison with the farmers themselves. These and other desirable innovations frequently lack the necessary governmental resources, but they will eventually be implemented, even though more slowly than is desirable.

Countries of Group 2 give more emphasis in their proposals to the more basic organizational aspects. Cyprus, for example plans to introduce daily agrometeorological bulletins by radio, using the combined services of its plant protection and meteorological services. Turkey has emphasized education and modernization of equipment and data collection. A general attitude was that there should be more input from the meteorological services to improve warnings, and in particular, to make more effective use of forecasts. The only country taking part in the survey which suggested a joint effort with other countries is Mozambique which plans to predict the migratory behaviour of pests such as the red locust, in conjunction with neighbouring countries.

8.9.2 Plans for improving dissemination methods

The countries may be divided into distinct categories. The developed countries are moving towards increased use and development of high technologies in their dissemination systems. The use of videotex, teletext and computer terminals will increase. Telephone systems will become more versatile, including automatic responders and in general there will be an increase in crop protection programmes. Group 2 countries emphasized the improvement of television facilities, in order to provide regular and special bulletins as on radio. However, some countries limited by lack of resources do not have an overall strategy at present to substantially improve services. Thus one notes the wide gulf separating developed from developing countries today in respect to overall improvement of dissemination and warning systems.

8.10 SUMMARY

Developed countries are entering an era in which it will become increasingly easy to disseminate in good time agrometeorologically-based products for crop protection.

There is a big difference at present between developed and developing countries in this sector. Even among developed countries there are
great differences in their level of operational crop protection. There are differences in

1. The level of crop protection knowledge used in preparing warnings and information.

2. Level of trained and skilled professionals.

3. The resources and financing to improve methods and to adopt more sophisticated methods.

4. The level of communication

Exchange of knowledge and international co-operation through all phases of crop protection systems that are agrometeorologically-based would certainly help to improve their value. However the transfer of operational schemes from developed to developing nations will remain impracticable while large disparities of resources exist between these countries.

8.11 REFERENCES


QUESTIONNAIRE ON DISPERSATION OF AGROMETEOROLOGICAL INFORMATION
FOR CROP PROTECTION ACTIVITIES

1. Do you have in your country an information system for crop protection?
   / yes / no /

   If your answer is 'yes',
   
1.1 for which crops, diseases and pests?
   
   crops          diseases          pests
   ----------------          ----------------          ----------------
   ----------------          ----------------          ----------------
   ----------------          ----------------          ----------------
   ----------------          ----------------          ----------------
   ----------------          ----------------          ----------------
   ----------------          ----------------          ----------------
   ----------------          ----------------          ----------------
   ----------------          ----------------          ----------------
   ----------------          ----------------          ----------------

   1.2 Does the information system use agrometeorological information?
   / yes / no /

   1.3 Are the outputs of the system published?
   / yes / no /

   1.3.1 If 'yes' what is the frequency of publication?
   Regular/During critical periods only

2. Are warnings for crop protection issued in your country?
   / yes / no /

   If your answer is 'yes',

   2.1 for which crops, diseases and pests?
   
   crops          diseases          pests
   ----------------          ----------------          ----------------
   ----------------          ----------------          ----------------
   ----------------          ----------------          ----------------
   ----------------          ----------------          ----------------
   ----------------          ----------------          ----------------
   ----------------          ----------------          ----------------
   ----------------          ----------------          ----------------
   ----------------          ----------------          ----------------

   2.2 Does the warning system use agrometeorological information?
   / yes / no /

   2.2.1 If 'yes' does the Meteorological Service have any part in the process of producing the warnings?
   / yes / no /

   2.2.1.1 If 'yes' please state the method of participation by the Meteorological Service.
2. Which organisation produces the warnings for crop protection?
   Meteorological Service/Crop Protection Service/Others (please specify)

3. If the information or warning systems use agrometeorological information, please write the names of the diseases and pests against the meteorological variables listed in the following table:

   Crop... (use separate sheet for each crop)

<table>
<thead>
<tr>
<th>Weather variable</th>
<th>Diseases</th>
<th>Pests (including weeds)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Information system</td>
<td>Warning system</td>
</tr>
<tr>
<td></td>
<td>Observed data</td>
<td>Forecast data</td>
</tr>
<tr>
<td>1. Temperature Max.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Day degree</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Duration above/below thresholds</td>
<td></td>
</tr>
<tr>
<td>2. Humidity</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>V. pr.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M. Hr.</td>
<td></td>
</tr>
<tr>
<td>3. Wind</td>
<td>Speed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dir.</td>
<td></td>
</tr>
<tr>
<td>4. Rainfall</td>
<td>Amount, Intensity</td>
<td></td>
</tr>
<tr>
<td>5. Surface wetness duration</td>
<td>From rain, dew</td>
<td></td>
</tr>
<tr>
<td>6. Soil moisture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Sunshine</td>
<td>Duration</td>
<td></td>
</tr>
<tr>
<td>8. Cloudiness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Others</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. Are warnings given for the first attack of diseases and pests?
   Diseases [yes / no /
   Pests   [yes / no /

4.1 If your answer is 'yes' for diseases, please give details
   ..............................................................
   ..............................................................
   ..............................................................
   ..............................................................
   ..............................................................

4.2 If your answer is 'yes' for pests, please give details
   ..............................................................
   ..............................................................
   ..............................................................
   ..............................................................
   ..............................................................

5. Are negative forecasts (forecast of periods free from diseases or pests) given for crop protection purposes?
   /yes / no /

5.1 If 'yes' please give details
   ..............................................................
   ..............................................................
   ..............................................................
   ..............................................................
   ..............................................................

6. Do you give any information or warning on the intensity of diseases or pests?
   Diseases [yes / no /
   Pests   [yes / no /

6.1 If 'yes', for diseases, please specify
   ..............................................................
   ..............................................................
   ..............................................................
   ..............................................................
   ..............................................................

6.2 If 'yes', for pests, please specify
   ..............................................................
   ..............................................................
   ..............................................................
   ..............................................................
   ..............................................................
7. Do you give any information or warning on the duration of disease or pests?
   Diseases / yes / no /
   Pests / yes / no /

   7.1 If 'yes' for diseases, please specify...........................
   ...........................................................................
   ...........................................................................

   7.2 If 'yes' for pests, please specify.................................
   ............................................................................
   ............................................................................

8. Do you have training/educational programmes in crop protection?
   for advisers / yes / no /
   for farmers / yes / no /

   8.1 If 'yes', please give details...........................................
   ..............................................................................
   ..............................................................................

9. Which of the following dissemination methods are used in your country for crop protection?

   9.1 Personal contact

   9.1.1 Nat. Service / yes / no /
   9.1.2 Agriculture Ministry / yes / no /

   9.2 Press / yes / no /
   9.3 Press / yes / no /

9.4 Broadcasting systems

   9.4.1 Radio / yes / no /

   9.4.1.1 If 'yes', are the crop protection bulletins broadcast regularly? / yes / no /
   9.4.1.2 If 'yes', how frequently? ...........................................
   9.4.1.3 If 'no', are they broadcast when needed? / yes / no /

   9.4.2 Television / yes / no /

   9.4.2.1 If 'yes', are the crop protection bulletins broadcast regularly? / yes / no /
   9.4.2.2 If 'yes', how frequently? ...........................................
   9.4.2.3 If 'no', are they broadcast when needed? / yes / no /

9.5 Teletext and Viewdata system / yes / no /

   9.5.1 If 'yes', please give details...........................................
   ..............................................................................
   ..............................................................................

9.6 Telephone / yes / no /
9.6.1 If 'yes', please indicate where calls are to be made for obtaining information or warnings?
   - To Met. Service/To Crop Protection Service/To Fixed No. for pre-recorded messages

9.7 Are there other methods for dissemination of information and warnings for crop protection in your country?

/ yes / no /

9.7.1 If 'yes', please give details.

10. Which organization distributes crop protection information and warnings in your country?
    Government/Others (please specify)

11. Are charges levied for the following services?

<table>
<thead>
<tr>
<th>Method</th>
<th>yes</th>
<th>no</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulletin</td>
<td></td>
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<tr>
<td>Personal contact</td>
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<td></td>
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<tr>
<td>&quot;Telephone call&quot;</td>
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</tr>
<tr>
<td>Teletext/Viewdata</td>
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<td></td>
</tr>
<tr>
<td>Telex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other (please specify)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*excluding telephone fee

12. What is the delay in getting operational written bulletins to the user?
   1 day
   2 days
   3 days
   greater than 3 days

13. What dissemination method is found to be most satisfactory in your country? (Please consider quality of material and the quickness of its arrival to the farmer)
    - Personal contact/Press/Post/Radio/Television/Telephone
    - Teletext/Viewdata/Telex/Others (please specify)

14. Are there plans to increase the efficiency of the information and warning systems by:
   14.1 Improving schemes for producing warnings? / yes / no /
   14.1.1 If 'yes', please give details

14.2 Improving methods of dissemination? / yes / no /
   14.2.1 If 'yes', please give details

THE QUESTIONNAIRE
15. Please attach published material or references to publications, bulletins, warning messages and any other material relevant to information schemes and warning schemes, that have been tried (add explanatory information, as required).

16. Please send examples or references to examples, where the economic benefits of crop protection schemes which use agrometeorological observations and information have been quantified.
COUNTRIES WHICH PARTICIPATED IN THE SURVEY

<table>
<thead>
<tr>
<th></th>
<th>Country</th>
<th></th>
<th>Country</th>
<th></th>
<th>Country</th>
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<tr>
<td>1.</td>
<td>Argentina</td>
<td>31.</td>
<td>Iraq</td>
<td>62.</td>
<td>Trinidad &amp; Tobago</td>
</tr>
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## COUNTRIES GROUPED ACCORDING TO THE EXTENT OF THEIR REPORTED CROP PROTECTION PROGRAMMES

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<td>Colombia**</td>
<td>Gambia*</td>
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<td>Guinea</td>
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<td>Mali*</td>
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<td>Mauritania**</td>
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<td>Egypt*</td>
<td>Morocco**</td>
</tr>
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<td>Qatar</td>
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<td>Germany (Fed Rep)*</td>
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<td>Fiji*</td>
<td>Tanzania*</td>
</tr>
<tr>
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<td>Guadalupe/Martínique (France)</td>
<td>Togo**</td>
</tr>
<tr>
<td>Japan*</td>
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<td>India*</td>
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<td>Yugoslavia*</td>
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<td>Reunion* (France)</td>
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<td>Switzerland</td>
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<td>Thailand**</td>
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</tr>
<tr>
<td></td>
<td>Turkey*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Uruguay**</td>
<td></td>
</tr>
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* Warning systems are reported with specific details
** Warning systems are reported, but details unavailable
## APPENDIX 8.3

### CROPS AND DISEASES INVOLVED IN THE REPORTED CROP PROTECTION SYSTEMS

<table>
<thead>
<tr>
<th>CROPS</th>
<th>DISEASES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cereals</strong></td>
<td>Powdery mildew (&lt;i&gt;Erysiphe graminis&lt;/i&gt;)</td>
</tr>
<tr>
<td>(winter and spring):</td>
<td>Rusts (&lt;i&gt;Puccinia spp.&lt;/i&gt;)</td>
</tr>
<tr>
<td>wheat</td>
<td>Leaf and glume blotch (&lt;i&gt;Septoria spp.&lt;/i&gt;)</td>
</tr>
<tr>
<td>barley</td>
<td>Leaf blotch (&lt;i&gt;Rhynchosporium secalis&lt;/i&gt;)</td>
</tr>
<tr>
<td>oats</td>
<td>Net blotch (&lt;i&gt;Pyrenophora teres&lt;/i&gt;)</td>
</tr>
<tr>
<td>millet</td>
<td>Eyespot (&lt;i&gt;Pseudocercosporella herpotrichoides&lt;/i&gt;)</td>
</tr>
<tr>
<td>sorghum</td>
<td>Root rot (&lt;i&gt;Corticium solani, Pythium spp.&lt;/i&gt;)</td>
</tr>
<tr>
<td></td>
<td>Scab (&lt;i&gt;Fusarium graminearum&lt;/i&gt;)</td>
</tr>
<tr>
<td></td>
<td>&lt;i&gt;Fusarium spp.&lt;/i&gt;</td>
</tr>
<tr>
<td></td>
<td>Snow blight (&lt;i&gt;Typhula incarnata, Fusarium nivale&lt;/i&gt;)</td>
</tr>
<tr>
<td><strong>Leguminous crops</strong></td>
<td>Leaf spot</td>
</tr>
<tr>
<td></td>
<td>Eyespot</td>
</tr>
<tr>
<td></td>
<td>Halo blight (&lt;i&gt;Pseudomonas medicaginis&lt;/i&gt;)</td>
</tr>
<tr>
<td></td>
<td>Scab</td>
</tr>
<tr>
<td></td>
<td>Bacterial wilt (&lt;i&gt;Corynebacterium flaccumfaciens&lt;/i&gt;)</td>
</tr>
<tr>
<td></td>
<td>Rust (&lt;i&gt;Uromyces phaseoli&lt;/i&gt;)</td>
</tr>
<tr>
<td><strong>Rice</strong></td>
<td>Blast (&lt;i&gt;Pycnographia oryzae&lt;/i&gt;)</td>
</tr>
<tr>
<td></td>
<td>Sheaf blight (&lt;i&gt;Corticium sasakii&lt;/i&gt;)</td>
</tr>
<tr>
<td><strong>Potatoes</strong></td>
<td>Late blight (&lt;i&gt;Phytophthora infestans&lt;/i&gt;)</td>
</tr>
<tr>
<td></td>
<td>Storage diseases</td>
</tr>
<tr>
<td></td>
<td>Soil born diseases</td>
</tr>
<tr>
<td><strong>Sugar beet and other beets</strong></td>
<td>Leaf spot (&lt;i&gt;Cercospora beticola&lt;/i&gt;)</td>
</tr>
<tr>
<td></td>
<td>Powdery mildew (&lt;i&gt;Erysiphe betae&lt;/i&gt;)</td>
</tr>
<tr>
<td><strong>Cotton</strong></td>
<td>Spot</td>
</tr>
</tbody>
</table>
## APPENDIX 8.3 (continued)

### CROPS

<table>
<thead>
<tr>
<th>Vegetables:</th>
<th>Diseases</th>
</tr>
</thead>
<tbody>
<tr>
<td>tomatoes</td>
<td>Early blight (<em>Alternaria solani</em>)</td>
</tr>
<tr>
<td>cucumbers</td>
<td>Late blight (<em>Phytophthora infestans</em>)</td>
</tr>
<tr>
<td>cabbages</td>
<td>Leaf spot</td>
</tr>
<tr>
<td>celery</td>
<td>Downy mildew (<em>Peronospora parasitica</em>,</td>
</tr>
<tr>
<td></td>
<td><em>Pseudoperonospora cubensis</em>)</td>
</tr>
<tr>
<td></td>
<td>Scab (<em>Cladosporium cucumerinum</em>)</td>
</tr>
<tr>
<td></td>
<td>Mosaic virus</td>
</tr>
<tr>
<td></td>
<td>Septoriose</td>
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</table>

<table>
<thead>
<tr>
<th>Fruits:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>apples</td>
<td>Powdery mildew (<em>Podosphaera leucotricha</em>)</td>
</tr>
<tr>
<td>pears</td>
<td>Scab (<em>Venturia spp.</em>)</td>
</tr>
<tr>
<td>cherries</td>
<td>Rusks</td>
</tr>
<tr>
<td>plums</td>
<td>Leaf spot</td>
</tr>
<tr>
<td></td>
<td>Blossom blight (<em>Monilia laxa</em>)</td>
</tr>
<tr>
<td></td>
<td>Fire blight (<em>Erwinia amylovora</em>)</td>
</tr>
</tbody>
</table>

| Peaches           | Scab (*Venturia carpophila*)                  |
| apricots          | Crown rot                                     |

| Citrus fruits     | Scab (*Elainoe fawcettii*)                    |
|                   | Canker                                        |
|                   | Melanose (*Diaporthe citri*)                  |

| Grapes            | Downy and powdery mildew (*Plasmopara viticola*, |
|                   | *Uncinula necator*)                           |
|                   | Ripe rot                                      |
|                   | Rust                                          |
|                   | Leaf spot                                     |

| Olive             | Crown gall (*Agrobacterium tumefaciens*)      |

| Banana            | Black Sigatoka (*Mycosphaerella fijiensis var. |
|                   | difformis*)                                   |
|                   | Sigatoka (*Mycosphaerella musicola*)          |
MAIN CROPS AND PESTS THAT ARE INVOLVED IN THE REPORTED CROP PROTECTION SYSTEMS

<table>
<thead>
<tr>
<th>CROPS</th>
<th>PESTS</th>
<th>CROPS</th>
<th>PESTS</th>
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<tr>
<td>Cereals</td>
<td>Aphids</td>
<td>Fruits</td>
<td>Worms</td>
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<tr>
<td>(including maize)</td>
<td>Army worms</td>
<td></td>
<td>Fruit moths</td>
</tr>
<tr>
<td></td>
<td>(Spodoptera spp., Mythimna</td>
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<td>Coding moth</td>
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<tr>
<td></td>
<td>seperata, etc)</td>
<td></td>
<td>(Laspeyrasia pomonella)</td>
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<tr>
<td></td>
<td>European Corn borer</td>
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<tr>
<td></td>
<td>(Ostrinia nubilalis)</td>
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<tr>
<td></td>
<td>Locusts</td>
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<td></td>
</tr>
<tr>
<td>Leguminous crops</td>
<td>Cutworms</td>
<td>Citrus fruits</td>
<td>Fruit moths</td>
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<td></td>
<td>Army worms</td>
<td></td>
<td>Red mite</td>
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<tr>
<td>Rice</td>
<td>Leaf roller</td>
<td>Grapes</td>
<td>Clearwing moth</td>
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<td></td>
<td>(Chaphaloroccis medinalis)</td>
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<td>Borer</td>
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<td>Stem borers</td>
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<td>Leafhopper</td>
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<td>Lobesia botrana</td>
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<td>Plant and grasshoppers</td>
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<td></td>
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<td>(Decladispa armigera)</td>
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<td>Aphids</td>
<td>Olives</td>
<td>Fruit moth</td>
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<td>Colorado beetle</td>
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<td>(Leptinotarsa decemliata)</td>
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<td>Cotton</td>
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<td>Borers</td>
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<tr>
<td>Vegetables</td>
<td>Cutworms</td>
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<tr>
<td></td>
<td>Beetles</td>
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<td>Diamond moths</td>
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<td>Tuber moths</td>
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</tr>
<tr>
<td></td>
<td>MIN</td>
<td>MAX</td>
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* "T" = THRESHOLD, "W" = WARNING, "A" = DURATION < THRESHOLD
1: 3-HOUR VALUES
2: MEAN
# Wheat and Other Cereals

## Observed Data

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Notes:
- * = Information
- W = Warning
- A = Duration < Threshold
# MAIZE AND RICE

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### Weather Conditions

- **Temperature**
- **Humidity**
- **Wind**
- **Rainfall**
- **Surface Wetness**
- **Sowing Date**
- **Growth Stage**
- **Disease**

### Forecast Data

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### Disease

- Fusarium
- Leaf Rust
- Pyricularia oryzae
- Pyricularia oryzae
- Pyricularia oryzae
- Leaf Blight
- Conticium fascianum
- Conticium fascianum
- Conticium fascianum

---

# FRUITS AND PEANUT

## Observed Data

| Country     | Temperature | Humidity | Wind | Rainfall | Surface Moisture | Duration | Others | Temperature | Humidity | Wind | Rainfall | Surface Moisture | Duration | Others | Disease                   |
|-------------|-------------|----------|------|----------|------------------|----------|--------|-------------|----------|------|----------|------------------|----------|--------|----------------|------------------|
| UK          | W           | *       | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| FRANCE      | W           | *       | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| AUSTRIA     | I           | *       | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| AUSTRIA     | W           | *       | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| CZECHOSLOVAKIA | W       | *       |       |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| ITALY       | W           | *       |       |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| YUGOSLAVIA  | W           |        | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| TURKEY      | I           | *       |       |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| CANADA      | W           | *       | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| POLAND      | W           |        |      |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| CANADA      | I           | *       | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| CANADA      | I           | *       |       |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| PORTUGAL    | W           | *       |       |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| GREECE      | W           |        | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| URUGUAY     | I           | *       | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |

## Forecast Data

| Country     | Temperature | Humidity | Wind | Rainfall | Surface Moisture | Duration | Others | Temperature | Humidity | Wind | Rainfall | Surface Moisture | Duration | Others | Disease                   |
|-------------|-------------|----------|------|----------|------------------|----------|--------|-------------|----------|------|----------|------------------|----------|--------|----------------|------------------|
| UK          | W           | *       | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| FRANCE      | W           | *       | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| AUSTRIA     | I           | *       | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| AUSTRIA     | W           | *       | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| CZECHOSLOVAKIA | W       | *       |       |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| ITALY       | W           | *       |       |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| YUGOSLAVIA  | W           |        | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| TURKEY      | I           | *       |       |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| CANADA      | W           | *       | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| POLAND      | W           |        |      |          |                  |          |        |              |          |      |          |                  |          |        |                           |
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| CANADA      | I           | *       |       |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| PORTUGAL    | W           | *       |       |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| GREECE      | W           |        | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |
| URUGUAY     | I           | *       | *    |          |                  |          |        |              |          |      |          |                  |          |        |                           |

## Disease

- Erwinia amylovora
- Ventura maculata
- Ventura indica
- Boeinga sencoria
- Rhizophora tragaeae
- Ventura oleascus
- Cercospora 400
- Cercospora 400

* 1 = Information  W = Warning  A' = Duration < C > Threshold
## GRAPES, BANANA AND CITRUS

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| AUSTRIA        | I   | ⋆   | ⋆   | ⋆   | ⋆   | ⋆ | ⋆   | ⋆   | ⋆ | ⋆   | ⋆   | ⋆ | ⋆   | ⋆   | ⋆   | ⋆   | Plasmopara viticola
| CZECHOSLOVAKIA | W   | ⋆   | ⋆   | ⋆   | ⋆   | ⋆ | ⋆   | ⋆   | ⋆ | ⋆   | ⋆   | ⋆ | ⋆   | ⋆   | ⋆   | ⋆   | Plasmopara viticola
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| URUGUAY        | W   | ⋆   | ⋆   | ⋆   | ⋆   | ⋆ | ⋆   | ⋆   | ⋆ | ⋆   | ⋆   | ⋆ | ⋆   | ⋆   | ⋆   | ⋆   | Anthracnose
| BANANA         |     |     |     |     |     |   |     |     |   |     |     |   |     |     |     |     | Sigatoka
| CITRUS         |     |     |     |     |     |   |     |     |   |     |     |   |     |     |     |     | Easyod Fawcett
| JAPAN          | I   |     |     |     |     |   | *   |     |   |     |     |   |     |     |     |     | Canker
| JAPAN          | W   |     |     |     |     |   | *   |     |   |     |     |   |     |     |     |     | Canker
| JAPAN          | I   |     |     |     |     |   | *   |     |   |     |     |   |     |     |     |     | Canker
| JAPAN          | W   |     |     |     |     |   | *   |     |   |     |     |   |     |     |     |     | Diaspom pinn.

"1" = INFORMATION   "W" = WARNING   "A" = CURATION / Threshold
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|              | SUGAR BEET       |               |               | Car什么都米呢。
| ITALY        | Y               |               |               |                       |
|              | TOMATOES, PEPPER |               |               |                       |
| GUADELOUPE   | W               |               |               |                       |
| BEANS        |                 |               |               |                       |
| KENYA        | Y               |               |               | Rabuabudge menindigia |
| KENYA        | Y               |               |               | Scab                  |
| KENYA        | Y               |               |               | Cutaneous granulomatous inflammation |

* = INFORMATION  \( W = WARNING \)  \( A = DURATION \& C = \text{THRESHOLD} \)
### FRUITS, CITRUS AND GRAPES

#### OBSERVED DATA

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#### FORECAST DATA

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<th>RAINFALL</th>
<th>SURFACE WETNESS DURATION</th>
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#### PEST

- *Laspeyresia pomonella*
- *Appel Wasp*
- *B. B.*
- *Laspeyresia*
- *Laspeyresia*
- *Laspeyresia*
- *Laspeyresia decemliata*
- *Lopchochloris Bicea Bala*
- *Citrus Mites*

#### GRAPES

<table>
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<tr>
<th>COUNTRY</th>
<th>TEMPERATURE</th>
<th>HUMIDITY</th>
<th>WIND</th>
<th>RAINFALL</th>
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#### PEST

- *Euxocis ambiguella*
- *Lepisma saccharina*
- *Euxocis ambiguella*
- *Lepisma saccharina*
- *European Grape Berry Morn*
## POTATO, VEGETABLES AND COTTON

### Observed Data

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<th>Country</th>
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<th>Humidity</th>
<th>Wind</th>
<th>Rainfall</th>
<th>Surface Moisture</th>
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<td>Cut Worms</td>
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<td>France</td>
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### Forecast Data

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<td>Guadeloupe</td>
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</table>

### Pest

- Aphids
- Cut Worms
- Diaphorina
- Lepidoptera decemlineata
- Acroleum Bronn

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* = Information  W = Warning  A* = Duration > Threshold  
1) Cabbage, Carrot, Onions  2) Tomatoes  
C* = Diamond Moths, Cabbage and Onion Maggots, Cabbage Worms, Carrot Weevil
## Cereals, Maize and Leguminous

### Observed Data

| Country       | Surface Moisture | Temperature | Humidity | VP | Rainfall | Surface Moisture | Temperature | Humidity | VP | Rainfall | Surface Moisture | Temperature | Humidity | VP | Rainfall | Surface Moisture | Temperature | Humidity | VP | Rainfall | Surface Moisture | Temperature | Humidity | VP | Rainfall | Surface Moisture | Temperature | Humidity | VP | Rainfall | Surface Moisture |
|---------------|------------------|-------------|----------|----|----------|------------------|-------------|----------|----|----------|------------------|-------------|----------|----|----------|------------------|-------------|----------|----|----------|------------------|-------------|----------|----|----------|------------------|-------------|----------|----|----------|------------------|-------------|----------|----|----------|------------------|
| Germany (DOR) |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |
| Canada        | W                |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |
| China         | W                |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |
| Tanzania      | W                |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |
| Australia     | W                |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |
| France        | W                |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |
| **Maize**     |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |
| Canada        | I                |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |
| Kenya         | I                |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |
| Mali          | W                |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |
| **Leguminous**|                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |
| Canada        | I                |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |             |          |    |          |                  |

* = INFORMATION  W = WARNING  A = DURATION > THRESHOLD

### Pest

- Aphids
- Pseudaphis aseptata
- Spodoptera exempta
- African quails
- Locust
- Ostrinia nubilalis
- Catophragmus robustus
- Spodoptera Root Worm
- Spodoptera
- European Stanker

**APPENDIX 8.51**
# RICE AND SUGAR CANE

## Observed Data

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<th>Country</th>
<th>Temperature</th>
<th>Humidity</th>
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</table>

<table>
<thead>
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<tr>
<td>Rice Borer:</td>
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<tr>
<td>Nilaparvata lugens</td>
</tr>
<tr>
<td>Rice Stem Borer: White &amp; Brown:</td>
</tr>
<tr>
<td>Planthopper:</td>
</tr>
<tr>
<td>Rice Leaf Beetle:</td>
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<tr>
<td>Stem Borer: Nilaparvata lugens:</td>
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<tr>
<td>Dodelloidea armigera:</td>
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<tr>
<td>Frog Hopper:</td>
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<tr>
<td>Heteroptera armigera:</td>
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</tbody>
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* = INFORMATION  W = WARNING  A = DURATION > THRESHOLD  1) INCLUDING CITRUS, MANGO, APRICOT
CHAPTER 9

ECONOMIC IMPORTANCE OF AGROMETEOROLOGY INPUT TO
OPERATIONAL CROP PROTECTION

9.1 INTRODUCTION

Previous chapters in this report included examples of agrometeorological contributions to operational crop protection schemes. Agrometeorology forms an important part of such schemes by signalling the timing of a spray, the dispatching of scouts to the site of a possible pest problem, the most appropriate weather conditions for spraying, and so on. However, it is not possible to separate the economic benefits of the agrometeorological inputs from the other inputs that form an integrated pest management package. Therefore the available information which is summarized in this chapter documents the overall economic impact of some crop protection schemes that have agrometeorological components.

Some estimates of the total loss of crop productivity to various pests are worth noting. Examples have been given already in Chapters 1 and 5. These and other reports on losses in wheat and rice (Ahrens et al., 1983; Saxena, 1983), cotton (Gledhill, 1976; Hawtree, 1980; Kumar, 1983), maize (Rose, 1976; Rodriguez-Arden et al., 1980; Wood et al., 1980) and sorghum (ICRISAT, 1982) demonstrate not only the enormous level of losses from pests and diseases that occur regularly, but also that these losses are not necessarily confined to the developing nations. For example, an evaluation in six European countries over an area of 929,000 hectares of vegetable crops suggested 3 per cent losses to animal pests, 11 per cent to diseases, and 10 per cent to weeds (Mathys, 1974). These figures are low in comparison with the work of Tolman and McLeod (1984) in Canada. For tomatoes grown without the use of herbicides in one treatment, without fungicides in another, and without insecticides in a third, they found yield reductions of 67 per cent owing to weeds and 31 per cent because of diseases (insects were not a problem). For onions the losses were 26 per cent due to insects, 100 per cent due to weeds, and 16 per cent due to disease. It is clear therefore, that effective crop protection is a worthwhile objective.

9.2 DIRECT BENEFITS

Direct benefits of crop protection schemes include savings of costs of chemicals when spray applications are reduced; savings of fuel; savings in depreciation and labour as spray equipment is not used in the field as often; and increases in crop yield or quality. An overall goal is the suppression of pest problems with the minimum possible expenditure. Agrometeorological input has particular impact in several situations. Such input may prevent mistiming of a spray application and thus avoid the washing away of the material by rain before it has had time to act, or the unnecessary use of a pesticide when the weather is unfavourable to the pest’s development. It may also prevent damage to off-target crops by suggesting periods when spraying should be avoided due to the likelihood of dangerous spray drifting. In the longer term, good agroclimatological advice based on weather records over many years can help to locate new plantings of crops in areas where the climate is unfavourable for the development of particular pests (Gerber and Lobregat, 1981). There are also some crops for which only one application of a pesticide can be afforded
in a growing season. The spray timing must therefore be exact, and indices computed from weather data (see examples in Chapters 2 and 3) can give important guidance concerning the optimum time to attack a particular pest.

Usually, operational crop protection is considered on the scale of farm units, but the internationally-supported locust control programme (Chapter 4) is an example of meteorological information being used in pest management over a huge geographic area, with the region of concern stretching from India to Africa. Bullen (1966, 1970) reviewed the crop losses caused by locusts and grasshoppers and concluded that control measures made a significant contribution to the reduction of the locust menace. It is said by many control staff that the problem is finding locusts, not killing them, and this is where meteorology plays such an important part. Because the development of a locust upsurge needs widespread, heavy rainfall at suitable intervals, weather information gathered from ground stations, radar and satellites can provide important guidance for limiting the areas requiring ground survey. In addition, when survey teams have identified a locust population upsurge, the weather information on wind and other factors governing turbulent dispersion is required to apply insecticides in the most effective manner.

The efficiency with which locust upsurges are located and controlled can affect the total numbers by a large factor, perhaps 100-1000 times (MacCuaig, 1969). Fig 9.1 shows theoretical relationships between locust numbers, time and the onset of a plague, which is defined as more than $10^{10}$ locusts. There is debate as to the most economical time to attack during an upsurge, since action too early results in too few insects killed per unit of insecticide: however, the early detection of breeding areas using weather information as a guide allows the maximum time for organization and planning of the attack strategy.

![Theoretical relationship between locust numbers, time and the onset of a plague](image)

**Figure 9.1** Theoretical relationship between locust numbers, time and the onset of a plague (after MacCuaig, 1969)

A, B and C indicate the increase in population when no control, moderate control or control operations at a very early stage in the upsurge occur.
To determine the economic benefits of locust control operations it is necessary to look at the losses when outbreaks have not been controlled. For example, the 1968 plague in Ethiopia consumed an amount of food that would normally represent about 70 per cent of the total calorific intake for the local population (MacCuaig, 1969). The total crops now potentially at risk are estimated at about US $30 billion. The average annual expenditure on desert locust survey and control is about US $15 million, which is about 0.05 per cent of the crop value at risk, and is very similar to the cost of running a fire brigade, to which locust control has often been compared (J. Roffey, 1985). The benefit/cost ratio for the meteorological input to the programme might be considered even greater, since this input is only a fraction of the total expenditure.

Estimates of the economic benefits of pest management can be made by calculating the savings in fuel, machinery depreciation, labour, and chemicals when the frequency of spray applications on a crop is reduced. The reduced spray schedule is compared to the older style of "insurance scheme" when sprays are applied at regular intervals, regardless of the weather or other factors that might have negated the need for a pesticide application. At the time of this report, the cost of fuel, labour and depreciation was estimated at about US $10 per hectare per spray in north America, with chemical costs ranging widely from about US $5-60, depending on the material.

Experience with viticulture in the largest grape growing region of Switzerland, near Valais, shows the cost of insecticide applications to be reduced by about 30 per cent using an integrated pest management scheme (Schmid, 1983). The matter of "economic aspects of integrated control" was reviewed for a number of other crops by Mathys (1974). He cites the following reductions in costs for 20 apple orchards in south Germany on traditional pest management programmes and 25 on schemes with integrated pest and weather observations (Table 9.1).

<table>
<thead>
<tr>
<th>Reduction of costs in apple orchards</th>
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</thead>
<tbody>
<tr>
<td>Fungicide</td>
</tr>
<tr>
<td>Insecticide</td>
</tr>
<tr>
<td>Labour and machines</td>
</tr>
</tbody>
</table>

Mathys (1974) also mentions savings of 40 per cent for integrated control of pests in a peach orchard in France, 18 per cent in Swiss apple orchards, and up to 50 per cent in Texas cotton fields. Weather-timed fungicide sprays on onions in Ontario, Canada, reduced spray frequencies by 47 per cent during the summers of 1977-1979 (Gillespie, 1981).

Boureau and Olivier (1984) showed that the number of applications of pesticide used to control apple scab could be reduced by between 15 and 30 per cent when meteorological data were used to determine the spray applications.

WMO has published two technical notes on the economic benefits of climatological services (WMO 424, 1975) or agrometeorological information (WMO 526, 1980) and both contain some information on the value of weather information in crop protection. Examples of annual cost reductions due to more effective timing of control measures using agrometeorological input were:
Potato blight (UK)  £1 million
Potato blight (Germany)  U.S. $3.5 million
Sugar beet (UK)  £1 million
Grapes (France)  FF 47 million

Such large amounts of money become more meaningful if they are expressed in terms of a benefit/cost ratio for the agrometeorological advice. The same WMO Technical Notes cite studies in the UK, France and Hungary which calculate benefit/cost ratios of 120:1, 49:1, and 27:1, respectively.

Another way of expressing the economic value of agrometeorological information for crop production that is particularly informative for growers, is to calculate savings per hectare when routine spray programmes are replaced by weather-driven pest warning services. Such calculations by the Irish Meteorological Service in 1982 yielded the following results:

Potatoes  £35 per ha per year
Wheat  £30 per ha per year
Barley  £25 per ha per year

The above reductions are quite significant, but savings due to integrated pest management are sometimes downgraded by comparing them with the total cost of crop production. Crop protection costs for apple, pear and peach in France have been estimated by Millaire (1974) as 14.5 per cent, 10 per cent and 9 per cent, respectively.

Therefore, any savings afforded by integrated crop protection will be even smaller fractions of the total production budget. For example, the economic benefits of pest monitoring, with a combination of visual and weather observations, were studied for carrots and onions in Ontario by Steineroff and Pfeiffer (1981). They concluded that the net benefit for the average grower was just a 1.7 per cent reduction in the total cost of production. However, a better idea of the significance to the grower can be gained by considering the dollar value of these savings, which was approximately Cdn $40 per hectare. Thus a farmer with 50 hectares would have $2,000 extra in his pocket at the end of the season. These figures were based solely on the spray cost savings in the area, minus the cost of running the crop protection programme, including scouts, professional advisers, and equipment. No attempt was made to place a monetary value on the additional indirect benefits described below.

The most effective weather-based crop protection schemes are likely to be those which use forecast as well as current or climatological data. In these circumstances more formal methods of assessing cost/benefit ratios are likely to have advantages over empirical schemes. Models like those used by Katz et al. (1982), Stewart et al. (1984) and Murphy et al. (1985) to estimate the value of weather information in the protection of fruit against frost, for example, should have applications here, particularly when probability forecast data are used. However, effective use of these formal methods of assessment is only possible when fairly exact relationships between weather, pest and disease progress and subsequent crop losses are available: previous chapters in this report have demonstrated that at present such data are rarely available.
9.3 INDIRECT BENEFITS

There are a number of additional benefits of good pest management schemes that use biological and agrometeorological data to maximize crop protection with minimum resources. These benefits are less tangible than those discussed above, but are probably even more important.

The first important benefit is that as chemical input to the environment is reduced by integrated pest management, there is a subsequent reduction in air, soil, and water pollution; a spinoff of this reduction is the lowering of pesticide residues in certain foods. Instances are known of overspraying that has resulted in rejections of farm products due to high pesticide residues. It is impossible to put a monetary value on this benefit.

The overuse of pesticides can also hasten the development of resistance in the target pest. It is difficult to estimate a cost for the loss of an effective chemical, but the time and expense for a manufacturer to develop, test and register a new chemical is known to be very great. These costs must ultimately be passed on to the consumers. Overuse of pesticides may also upset the natural ecological balance of the field or orchard so that beneficial predators are killed and new pests emerge as the old pest is controlled.

If the number of trips into the field with spray machinery can be reduced with rational crop protection schemes, the result will be less soil compaction.

Finally, the fewer times that pesticides need to be applied, the greater the overall safety that is achieved.

9.4 CONCLUSIONS

It is not difficult to show the economic benefits of crop protection schemes that combine the use of biological and agrometeorological data to provide effective pest management with a high degree of efficiency and safety. The savings in spray costs alone are sufficient to cover more than the costs of running an integrated pest management programme. For example, the Canadian experience of a $40 net benefit per hectare applied to the 929,000 ha of European vegetable land mentioned in the introduction to this chapter, would amount to Cdn $37 million. The reduction in amount of applied pesticides have been between 15 per cent and 50 per cent in the examples cited: this translates into substantial additional monetary savings associated with reduction of pollution, avoidance of pesticide residues in food, postponement of resistance development in target pests, maintenance of beneficial predator populations, reduction in soil compaction by spray machinery, and enhancement of safety on the farm. There is no question that the benefits of the biological and agrometeorological services required in an operational crop protection scheme vastly outweigh the costs.


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CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

The distribution, development and number of pests and diseases are closely linked to meteorological factors, and so no fully effective crop protection scheme can be developed and run without agrometeorological inputs.

The preceding chapters have demonstrated the very different roles which weather plays in its influence on different pests and diseases. Consequently, optimal crop protection measures require the development of a large number of different strategies and tactics, which have to reflect not only the controlling meteorological influences but also a variety of other factors, for example, the value of the crops, availability of resources (including meteorological data, agrometeorologists, biological/extension service scientists, equipment and capital) and the local communication network.

A major obstacle in setting up sound, agrometeorologically-based crop protection schemes is often an inadequate understanding of the biological response to meteorological factors of the pest or disease being considered. This is true not only of relatively obscure local pests or diseases, but also of many of the widespread major pathogens. To improve this fund of biological knowledge is an important, and costly, challenge.

In those cases where the biological responses to weather have been adequately investigated, a number of important difficulties have to be faced when setting up the corresponding crop protection scheme. First from the agrometeorological standpoint is the likely lack of detailed, frequent meteorological data from a closely spaced network of stations that will usually be required when the pest or disease development is linked closely with rainfall or surface wetness; second the derivation from the standard data of the microclimate actually experienced by the pathogen; and finally the establishment of an organizational structure and a communication system to allow operational interaction between meteorologists, plant pathologists, entomologists, weed scientists, and the timely and effective dispatch of unambiguous advice to farmers. In-crop sensing removes some problems but poses further others because the farmer might then have to make his final crop protection decisions without assistance from biological scientists and on the basis of meteorological data from a measuring system for which any shortcomings in performance might go unnoticed.

There is no doubt that the developments in "information technology" now taking place in many countries make it easier for farmers to participate in agrometeorologically based schemes for crop protection. This new technology allows timely and cheap dissemination of advice, in substantial quantities when required. The methods employed can be highly automated, and this in turn encourages the development of fully automated operational data bases that produce, cheaply and at regular intervals, predictions of likely pest and disease development from inputs of current and forecast meteorologi-
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cal data. Such systems produce results only as good as the relationships they use to describe the biological responses to meteorological factors, which is a further stimulus to biological scientists and agrometeorologists to explore and refine the relationships currently in use, and to develop many more, to the point where all important pests and diseases will be considered.

It is unfortunate that official organizational structures within countries sometimes make it more difficult to develop operational crop protection schemes than would be the case in the ideal situation. In Europe, for example, adjacent countries often grow similar crops, with similar problems from diseases and pests, but have entirely different advisory schemes for crop protection. There is no doubt that closer relationships between countries would be beneficial in sharing knowledge and experience and so leading to the best operational services. Even within a country the links between meteorologists and the biological scientists and extension services need to be much stronger than they usually are at present.

Substantial resources are needed to develop new or enhanced crop protection schemes: those actually available always fall short of demand. There is a strong case, therefore, for collaboration between countries that would lead not just to the exchange of information but also to the rationalization of research and development programmes in order to avoid unnecessary duplication of effort. Agrometeorologists have an important role here, to recognize the shortfalls of biological knowledge in the context of crop protection, and to encourage biological research between countries that is complementary rather than competitive.

In the developing nations, where agriculture is usually an even more vital industry economically than in developed countries, the requirements for effective crop protection schemes are especially important. Unfortunately, many of the methods and techniques now in use or being devised in the developed nations, are largely inappropriate elsewhere because they depend on a number of resources that are not available to most of developing nations. Difficulties are often compounded by the lack of a cold season which can provide an annual pause in pest and disease development, although a dry season may perform the same function.

The role of the agrometeorologist in the case of cash cropping is likely to be very different from his role as regards subsistence farming. For the former the use of chemical control measures will usually be possible, and the agrometeorological input to crop protection schemes would often be to ensure that spray applications are timed to minimize overdosing and maximize effectiveness. Chemical control measures are likely to be beyond the resources of subsistence farmers, for whom the agrometeorologist's role is likely to be more strategic, for example to develop schemes for the timing of sowing and weeding in relation to expected rainfall patterns so as to minimize pest and disease incidence over the growth cycle of crops.
It is encouraging to see the success of the international monitoring and warning scheme for locusts run under the auspices of the Food and Agriculture Organization. Here a relatively small group of scientists, using synoptic data from many nations, and more recently satellite information also, provide an exceptionally cost effective service. Very important among the synoptic data are rainfall amounts, but these are often available only erratically from some areas. Accordingly agrometeorologists must make the importance of these data clear to their National Meteorological services, in order to encourage the maintenance of full synoptic observing programmes and the equally consistent international transmission of the observations.

The survey on the production and dissemination of information, which was carried out to assist the production of this report, produced an incomplete response, as surveys usually do. However, it has provided much useful information and in particular has demonstrated the very limited use of forecast agrometeorological information in most operational crop protection schemes. There is clearly much scope for improving existing and new schemes by employing forecast data.

10.2 RECOMMENDATIONS

1. Biologists should be encouraged to investigate those aspects of the development of significant pests or diseases that at present are not well enough understood to allow a fully satisfactory description of the response of these organisms to meteorological factors.

2. At least regional (international) co-ordination of the work of biologists studying the influence of meteorological factors on the development of significant pests and diseases is most desirable. National coordination of such activities, where it does not exist already, is equally important.

3. Agrometeorologists should attempt to ensure that operational crop protection training courses in their countries include appropriate information or instruction on the meteorological aspects.

4. More forecast meteorological data need to be incorporated in operational crop protection schemes.

5. The importance of synoptic rainfall data in locust monitoring cannot be overstressed: countries disseminating this information only erratically should be requested to meet their WMO commitments in this respect.

6. Full advantage should be taken of developments in data gathering by remote sensing: for example, centrally organized crop protection schemes can use operational radar rainfall data in order to provide local estimates of rainfall and (by inference) leaf surface wetness; rainfall information obtained indirectly from satellite imagery has many application also.

7. Where biological responses are properly understood, agrometeorologists should take the lead in exploring the use of special on-farm or local meteorological stations with automatic data processing in order to give farm-specific advice on operational crop protection.
8. Operational crop protection schemes should make the best use of "information technology" to provide timely, cheap and accurate advice fully supported by meteorological data.

9. A sponsor should be sought to organize and host an international conference on agrometeorological aspects of operational crop protection, with sessions to include at least the topics considered in Chapters 2 to 9 of this report.

10. On a shorter timescale than the previous recommendation, sessions on the topics of dissemination of crop protection warnings and information, and the economic importance of agrometeorological information in operational crop protection should be included in an appropriate conference.

11. Copies of this report should be distributed by Members to all authorities and official organizations involved with crop protection in their countries.
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